Applied Thermal Engineering 78 (2015) 289–302

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Studies on the effects of varying secondary gas properties in a low entrainment ratio supersonic ejector

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HIGHLIGHTS

- Dilution cum purge ejector is studied which has applications in fuel cell technology.
- Key challenges are differing secondary and primary gas at low entrainment ratio.
- Air, Helium and Argon used as secondary gas with primary gas as air.
- Valid solution domain of control volume method is highly dependent on secondary gas.
- Pressure profile and entrainment ratio are strong functions of secondary gas.

ARTICLE INFO

Article history:
Received 16 July 2014
Accepted 22 December 2014
Available online 30 December 2014

Keywords:
Supersonic ejector
Dilution cum purge ejector
Fuel cells
Secondary gas properties
Control volume method
Gaseous mixing

ABSTRACT

A dilution cum purge ejector for application in fuel cells represents a domain of ejector operation involving low entrainment ratio with differing secondary and primary gas; which is hardly investigated and a cohesive design framework is not readily available. We comprehensively study a constant area ejector using analytical, experimental and numerical tools at low entrainment ratio (0.004–0.065) with Air, Helium and Argon as secondary gas while the primary gas is Air. For the first time, limits of operating parameters used in control volume method to design the ejector are found to be highly dependent on the secondary molecular weight. The entrainment ratio in the ejector (low for Helium and high for Argon) is affected by the molecular weight and the static pressure within the ejector (low for Air and high for Argon & Helium) by the gamma of the secondary gas. Sufficient suction pressure (0.3–0.55 bar) is generated by the ejector thereby preventing any backflow of secondary gas at all primary stagnation pressures (1.5, 2.2 and 3.1 bar). Numerical results agree well with experimental results. The ejector is shown to completely dilute and purge the secondary flow, meeting all key design requirements.

1. Introduction

A supersonic ejector is a simple gasdynamic device. The suction generated by a primary flow expanding through a nozzle into a variable area duct is used to entrain and pump a secondary flow by means of momentum and energy augmentation. The foremost advantages of ejectors are absence of moving parts; and simplicity of design and operation. Ejectors have been used extensively; starting from the earliest use of steam ejectors as vacuum generators in steam condensers of power plants, thrust augmenting ejector for aircrafts [1,2], a replacement to compressors in refrigeration technology [3], a device to reduce starting loads and generate high altitude conditions in aerodynamic test facilities [4,5], pressure recovery system for gasdynamic lasers [6], to name a few. Very recently, the use of ejectors in thermal power cycles for waste heat recovery have been investigated [7]. Fuel cell technology is considered a viable eco-friendly alternative to the current fossil fuel based power production systems. The ejector can be used for recirculating excess fuel from the fuel cell stacks to minimize fuel consumption. An ejector recirculation system was investigated for application to a 1 MW fuel cell system [8]. Further, the technology of fuel cells is being adapted for transport applications in Fuel Cell Vehicles, which has generated significant interest in the automobile industry [9]. Hydrogen has been found to be the most suitable fuel given its high calorific value and the development of safe storage

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http://dx.doi.org/10.1016/j.applthermaleng.2014.12.053
1359-4311/

technologies [10]. Fig. 1 shows a typical fuel supply system to the fuel cell. Hydrogen fuel is supplied from high pressure storage devices to the fuel cell stacks where it undergoes electrochemical reactions with air supplied from the ambient thereby generating power and water as by-product. Excess, unreacted hydrogen is recirculated back to avoid wastage of fuel. Studies were carried out to implement an ejector based hydrogen recirculation system [11]. Previous work by the authors dealt with optimization of a supersonic hydrogen ejector for fuel recirculation purposes [12].

In this work the authors focus on a different segment in the fuel cell circuit – the purge system. To explain in brief, during the course of its operation the anode becomes contaminated with water and nitrogen which lowers the efficiency of the fuel cell operation. It becomes necessary to periodically purge the anode and when doing so hydrogen is also exhausted to the ambient. This hydrogen has to be rendered safe by sufficient dilution either with some chemically inert gas like nitrogen or deoxygenated air from the fuel cell itself, else there is a risk to safety from the highly inflammable hydrogen. Further, it should be ensured that chances of backflow are negligible. These requirements point towards the ejector as a suitable passive device that can mix hydrogen with the dilutant as well as purge it to the ambient.

Conventionally, the performance of the ejector is described in terms of entrainment ratio (ω) – ratio of the secondary mass flow rate to the primary mass flow rate, the stagnation pressure ratio (SPR) – the ratio of the primary flow stagnation pressure to the secondary flow stagnation pressure and the compression ratio (CR) – the ratio of the pressure at the exit of the ejector to the secondary flow stagnation pressure. The requirements of a dilution cum purge ejector are unique in many respects compared to other ejectors that have been investigated. The highlighting factor is that the molecular weight of the secondary gas is different from the primary gas. Majority of literature on the analysis and design of ejectors deal with scenarios where both primary and secondary gases have the same molecular weight. The operating conditions of the purge ejector are such that stagnation pressure available to the primary flow is limited, but simultaneously sufficient suction pressures are to be generated at the secondary flow so that backflow does not occur. This in turn leads to high compression ratio upon pressure recovery to the ambient when the flow is finally purged out of the ejector. An important point is that the entrainment ratio is very small (≈ 0.01), since the dilution levels required are about 1%. Since the density of the secondary gas is very low (especially when considering hydrogen), the sizes of ducts are significant even at small secondary flow rates. The analysis of ejectors has in general considered moderate to high entrainment ratios in comparison to the current requirements. Thus, though an overall framework for the design of gaseous ejectors exists in open literature its utility has never been extended to the regime of multiple molecular weight gases and very low entrainment ratios. This motivated the authors towards a comprehensive investigation on gaseous supersonic ejectors for dilution cum purge applications. Thus, analytical, numerical and experimental studies are carried out on dilution cum purge ejectors. The primary objective of this study is to understand the effects of having different molecular weight gases as the primary and secondary flow in a low entrainment ratio supersonic ejector. Therefore, helium, argon and air are used interchangeably as the secondary gas to bring out the effects of using low and high molecular weight secondary gas with the primary flow being air. The eventual use of a dilution cum purge ejector is in hydrogen fuel cells for diluting hydrogen. Here this flow scenario is depicted by using Helium which is a low density, low molecular weight gas comparable to hydrogen and is safe for laboratory experiments.

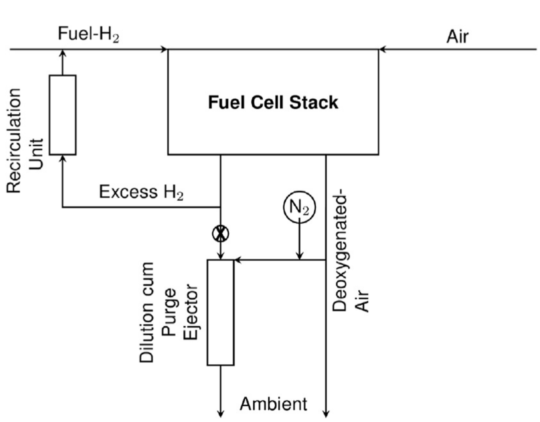

Fig. 1. Schematic representation of a typical fuel cell circuit.

First we describe the development of the control volume technique to design a gaseous ejector wherein the primary and secondary flows have different molecular weights. When using this procedure to design a low-entrainment ratio ejector we discover that there are limitations to the domain of operating conditions that can be used. From these considerations we evolve a methodology to design the dilution cum purge ejector. The final geometry that we arrive at is fabricated and its performance is tested in a supersonic ejector test facility. We conduct numerical investigations using Ansys Fluent CFD package to supplement the experimental results and understand the details of flow features within the ejector. The influence of secondary flow properties on the performance of the ejector is brought out from the experimental trends. We observe significant difference between the experimental and analytical performance curves. One of the reasons for the observed difference is the possibility of the primary flow expanding and impinging the mixing duct wall. This flow regime is similar to a base flow behind a backward facing step in supersonic flow but with a secondary bleed flow. Therefore, a correction to the control volume analysis using the base flow theory is discussed. We find that the trends obtained from CFD and experiments are in good agreement. We establish that complete dilution of the secondary flow does indeed take place by using the mass fraction profiles obtained from CFD. The details of the design procedure, experimental setup, numerical computations and a discussion of the results are detailed in this article.

2. Design methodology for a low entrainment ratio supersonic ejector with different primary and secondary gas

2.1. Control volume analysis of a gaseous ejector

Many articles have dealt with the design of ejectors using control volume techniques. The comprehensive report by Addy et al. [13] classified various operating regimes and appropriate control volume models for predicting the operation of the ejector were given. Critical or choked operation of the ejector is a key operating point, wherein the secondary flow undergoes gasdynamic choking within the ejector passage thereby rendering the mass flow through the ejector unresponsive to further lowering of back-pressure. Often this is the design operating point since the mass flow through the supersonic ejector becomes a maximum for the given upstream conditions. The Fabri choking theory [14] which was found suitable for a wide range of operating conditions, is employed to predict this operating point. Many variable area mixing duct geometries can be constructed of which some are classified into categories such as the constant pressure mixing duct and constant area mixing duct. The constant pressure mixing duct uses a varying area duct such that the pressure during mixing