EXPERIMENTAL INVESTIGATION OF SCALE EFFECTS IN MULTI-STAGE JET EJECTORS

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Abstract: Three microfabricated multi-stage jet ejectors were tested. Each axisymmetric nozzle was fabricated using electro-discharge machining to create throat diameters of 63 um,187 um and 733 um with a design expansion ratio of 2.5:1 and total ejector area ratio of 9. The experimental data using nitrogen gas as the motive fluid indicate that the ejector can produce a sufficient suction draft to enable its substitution for or augmentation to high speed turbomachinery in micro engine applications. The data also suggest that the two-stage ejectors do not outperform their single-stage counterparts of equal area ratio, perhaps because different stage-wise area ratios were used for the test pieces being considered.

Keywords: multi-stage ejector, jet ejector, micro pump

NOMENCLATURE

ρ	Density
$\dot{m}$	Mass flow
u	Axial velocity
A	Area
a	Area ratio, $A_{d,2}/A_{m,1}$
C_f	Thrust Coefficient
D	Diameter
L	Length
M	Mach number
P	Static pressure
P_t	Total pressure
Re	Reynolds number
α	Entrainment ratio
μ	Dynamic viscosity
γ	Ratio of specific heats
ε	Nozzle area ratio

Subscripts

m	Motive, or primary
s	Suction, or secondary
d	Discharge, or combined
$isen$	Isentropic

Superscripts

*	Throat

INTRODUCTION

Since the mid-1990's there has been an active effort to develop hydrocarbon-fueled power generation and propulsion systems on the centimeter scale or smaller. Designers have investigated microscale gas turbines, turbochargers, rotary internal combustion engines, and rockets [1-4]. These devices typically involve high-speed turbomachinery or other rotating parts, attendant seals,thermal isolation mechanisms, and high speed bearings.

Non-rotating pumping devices, such as jet ejectors and injectors, can serve as alternatives to turbomachinery, supplementing or eliminating high-speed components in microscale turbogenerators and rockets to enable the fabrication of power-MEMS devices that do not rely on moving parts. For example, ejectors and injectors can be used to implement a microscale steam locomotive engine, whose only moving part is a piston [5] or low-speed gas turbine used for power offtake [6,7], or to enable a microrocket requiring only a static structure [8,9]. The resulting reduction in complexity affords the designer a simple start-up protocol, robust operation, and the flexibility to use microfabrication processes such as isotropic wet chemical etching that offer comparatively poor tolerances.

Prior work has demonstrated that microscale single-stage jet ejectors can meet the gas pumping requirements of power-MEMS devices and can serve as a viable substitute for turbo-compressors [6,7] or vacuum pumps [10-11]. Investigators have also developed multi-staged lobed ejectors for thrust augmentation and heat signature suppression on turbofan and rotary wing aircraft [13]. The findings demonstrate improved efficiency over single-stage systems of the same area ratio, and for three-dimensional lobed mixer geometries, reduced mixing length requirements.

This paper reports on experiments performed on microscale two-stage ejectors of similar geometry, which feature three different motive nozzle throat diameters of 63 um, 187 um and 733 um.

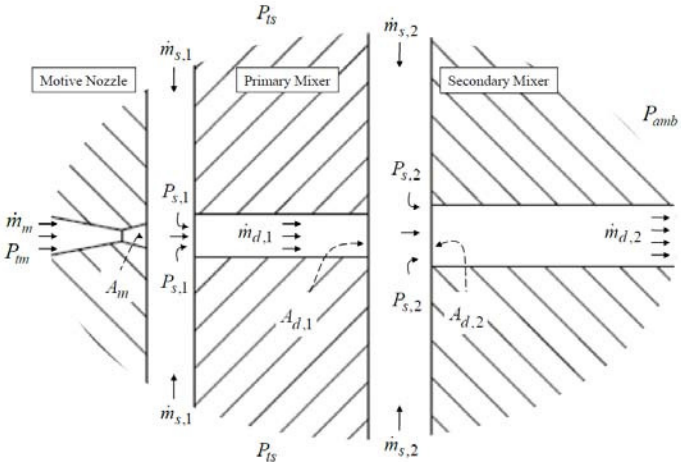

Fig. 1: Two-stage ejector schematic and flow paths

APPROACH

The motive nozzle is a 1-D axisymmetric converging-diverging nozzle. The diverging section for the nozzle produces a design expansion ratio of 2.5:1. Table 1 identifies the ejector design geometry, and Tables 2 and 3 compare this design geometry to the manufactured geometries for the nozzle and ejector assembly, respectively. Figure 1 depicts the ejector assembly, which consists of the motive nozzle, primary and secondary mixers. Electro-discharge machining (EDM) [6,7,14] was used to fabricate the nozzle geometries of Figures 3a-3c in stainless steel.

Table 1: Ejector design geometry

Expansion Ratio, ε	Expansion Angle, θ	Nozzle L/D*	Area Ratio, a	Mixer L/D
2.5	15°	4.3	9	4

Table 2: Design versus realized nozzle geometry

Motive Nozzle	Design Throat Diameter	Design Expansion Ratio, ε	Actual Throat Diameter	Actual Expansion Ratio, ε
Small	50 um	2.5	64 um	4.2
Medium	168 um	2.5	187um	2.7
Large	755 um	2.5	733um	2.2

Table 3: Design versus realized ejector geometry

Nozzle Exit Diameter, D_m	Design Area Ratio $a=A_{d,2}/A_{m,1}$	Actual Area Ratio $a=A_{d,2}/A_{m,1}$
129 um	9	7.6
309 um	9	9
1,097 um	9	9

Using the notation from Fig. 1, we define the total entrainment ratio as the ratio of the sum of suction mass flows to the motive mass flow.

$$\alpha \equiv \frac{1}{\dot{m}_{m,1}} \sum_n \dot{m}_{s,n} \qquad (1)$$

Using $A_d=A_m+A_s$ for each stage, we define the total ejector area ratio, which can also be expressed as a product of the stage-wise area ratios.

$$a \equiv \frac{A_{d,2}}{A_{m,1}} = \left(1+\frac{A_{s,1}}{A_{m,1}}\right)\left(1+\frac{A_{s,2}}{A_{m,2}}\right) \qquad (2)$$

For the ejectors tested here, $A_{s,1}/A_{m,1}=3.5$, $A_{s,2}/A_{m,2}=1$.

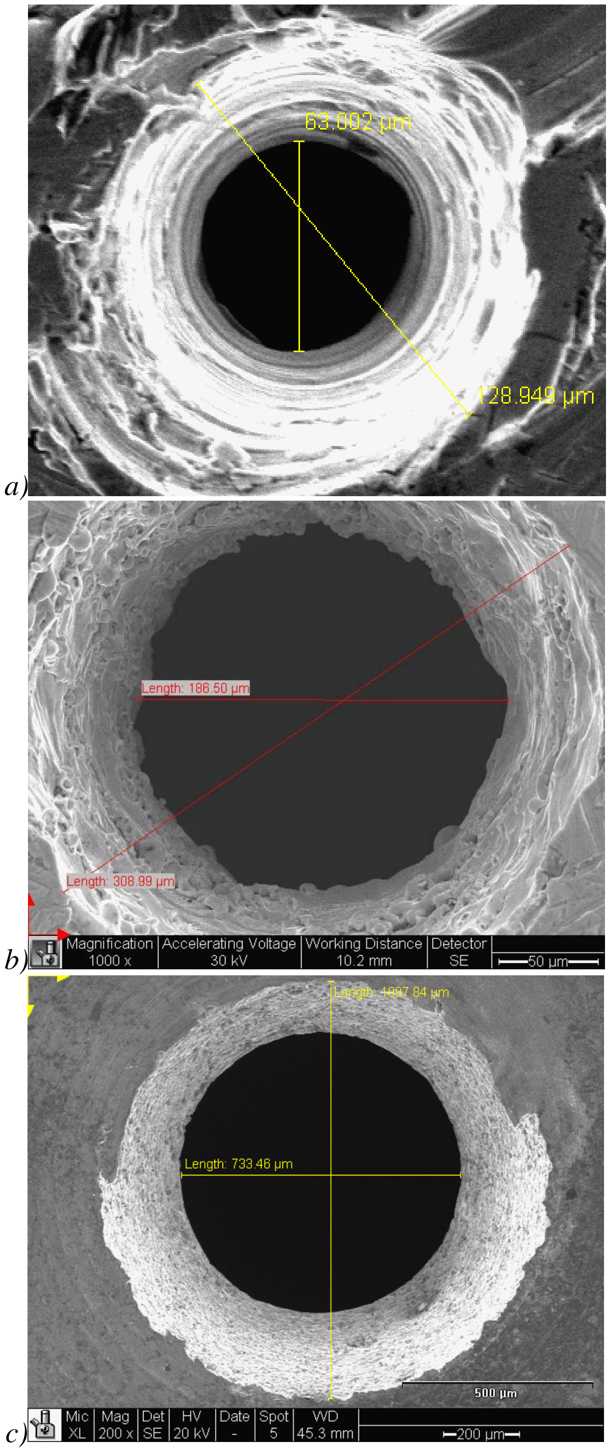

Fig. 2: Realized geometry for ejector motive nozzles. SEM images of a) 63 µm nozzle, b) 187 µm nozzle, c) 733 µm nozzle.

Results

Experiments were carried out using a test rig similar to [6,7], where nitrogen gas was supplied to the motive nozzle at a fixed pressure, and entrainment ratio was varied using a needle valve to throttle the suction fluid, which was measured using an MKS Alta-180 mass flow meter with a 0-20,000 sccm range. The motive fluid mass flow rate was computed using isentropic flow through the motive nozzle, which previous experiments have shown to be within a few percentage points of measured flow rates [6,7,16].

Fig. 3 shows suction draft versus entrainment ratio for the set of ejectors.

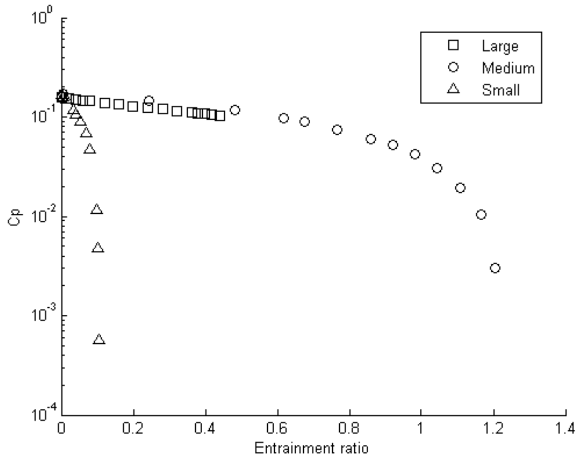

Fig. 3: Measured suction draft vs. entrainment ratio

DISCUSSION

As seen from Fig. 3, the suction draft of the 63 um throat ejector falls off at lower entrainment ratios than the 187 um or 733 um ejectors. Prior work on single-stage ejectors predicted the onset of scale effects for throat diameters as small as 10um for throat Reynolds numbers near 1,300 and mixer Reynolds numbers near 400 [6]. Other investigations of two-dimensional micronozzle measurements report weak viscous losses for Reynolds numbers near 2,000 [15]. Using the Reynolds number computed at the motive nozzle throat, we can compute the secondary mixer Reynolds number based on geometry and entrainment ratio.

$$\mathrm{Re}_{D_{d,2}} = \mathrm{Re}_{D_m^*} (a\varepsilon)^{-1/2} (\alpha + 1) \quad (3)$$

Using Eq. 3, values for the Reynolds numbers are computed over the range of measured entrainment ratios and are summarized in Table 4.

Table 4: Throat and secondary mixer Reynolds numbers

D_m^*	$\mathrm{Re}_{D_m^*}$	$\mathrm{Re}_{D_{d,2}}$
63 um	8,300	1,500-1,600
187 um	24,200	4,900-10,700
733 um	94,800	21,000-30,000

The behavior seen for the 63 um ejector results because the nozzle is over expanded, with an expansion ratio of 4.2 (Table 2) which reduces the nozzle exit velocity, as seen by invoking the conservation of momentum in the form of the isentropic thrust coefficient in equation 4.

$$C_{f,isen} = \frac{(\dot{m}_m u_m)_{isen} + (P_m - P_s) A_m}{P_{t,m} A_m^*} \quad (4)$$

The pressure matching term is computed using the nozzle exit plane static pressure, and the static pressure of the ambient, which for the case of the ejector is taken to be the suction fluid static pressure. When the nozzle exit plane static pressure drops below its surrounding ambient, the exit stream decelerates.

Fig. 4 plots computed thrust coefficients across measured entrainment ratios which correspond to measured suction pressures. We see that the effect of over expansion for the 63 um throat nozzle results in different behavior compared to the 187 um and 733 um nozzles, both of which have expansion ratios near design (Table 2) in comparison.

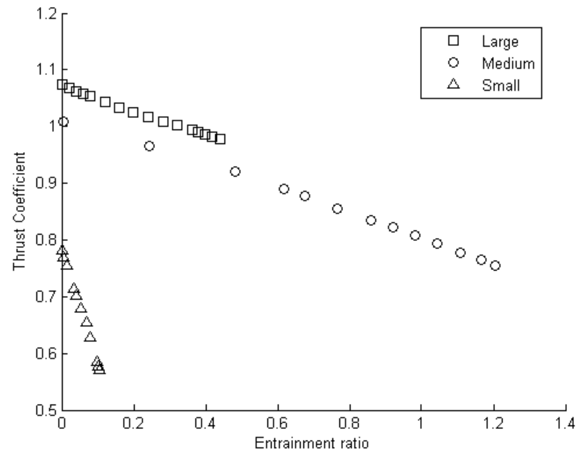

Fig. 4: Computed isentropic thrust coefficients vs. entrainment ratio

Previous work on multi-stage ejectors [13] showed improved efficiency for multi-stage ejectors, which manifests by creating higher suction draft than a single-stage given the same motive total pressure and area ratio. This work employed the same area ratio across both stages for a two-stage ejector also used shorter mixer length-to-diameter ratios (0.5-1) than conventional ejectors due to the presence of three-dimensional lobes in the mixer. The lobes generate streamwise vorticity, promoting momentum exchange between the higher velocity motive stream and the lower velocity secondary stream[12,13] in the shear layers formed when the two streams merge.

The current two-stage ejector results presented here do not outperform single-stage ejector results with the same overall area ratio from [6] and similar Reynolds numbers, which may be due to the difference in stage-wise area ratios. The primary and secondary area ratios were different for the test pieces considered here, which may inhibit any benefits of multi-staging.

CONCLUSIONS AND FUTURE WORK

A multi-stage ejector was tested at three different length scales (63 um, 187 um, 733 um) using nitrogen gas to motivate and entrain ambient air. The multi-stage ejectors performed similarly to single-stage ejectors of the same overall area ratio. Equal stage-wise area ratio may allow for superior performance to single-stage ejectors, but the data presented here for the case of unique stage-wise area ratios suggest negligible differences in ejector performance. Performance for the 63 um ejector deteriorated due to motive nozzle over expansion.

Future work will investigate the lower scale limits of multi-stage ejectors and the effects of different stage-wise area ratio on performance.

For applications when volume or weight constrains design, it is also suggested to implement lobed mixers to provide a reduction in ejector volume [13], which can be implemented using standard two-dimensional etching techniques or micro-machining.

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