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Comparison of novel variable area convergent-divergent nozzle performances obtained by analytic, computational and experimental methods

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ABSTRACT

Different applications of a variable area convergent-divergent nozzle are found in various parts of the industry. This paper presents the development of a new design methodology for a variable area convergent-divergent nozzle, to maintain constant nozzle area ratio for different values of mass flow rates. The validation of the presented model was carried out on an example supersonic ejector using experimental, numerical and analytical data. Analytical (one dimensional) and computational fluid dynamics models showed satisfactory prediction performance in comparison with the experiment. The average entrainment ratio error was between 10% and 7%, respectively. Results confirmed that the velocity of the primary fluid at the nozzle outlet is in accordance with the one dimensional analysis. Although disturbances (strong and weak shock waves) are visible, their effects are negligible. Also, supersonic ejector performances are presented through relations between entrainment ratio, outlet pressure and spindle position. Disadvantages of variable area nozzle utilization in ejector applications are emphasized.

1. Introduction

Modern technological efforts are primarily influenced by sustainability, concerning environmental problems and energy savings. Utilization of waste and low-grade thermal energy has been an area of interest for researchers and scientists over many years [1], with many examples in the literature (e.g. [2,3]). Specific topics connected with the combustion of very dangerous, explosive, toxic or low caloric value waste gasses have been studied recently (Zhou et al. [4] and Friesenhan et al. [5]). One of the ways of using such gases is by mixing them with high-pressure gas, to make a mixture which is safer or with higher exergy value. This is commonly achieved using supersonic gas ejectors.

Many different studies concerning the optimization of ejector design for various process fluids have been performed. Huang et al. [6] successfully developed a widely used one dimensional (1-D) model for prediction of supersonic ejector

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Nomenclature

$\dot{m}$, kg/s	mass flow rate;
A, m^2	cross-section area;
a, m/s	speed of sound;
C_p, J/K	heat capacity at constant pressure;
CR	compression ratio;
D, m	diameter;
ER	entrainment ratio;
K	constant;
k, m^2/s^2	turbulence kinetic energy;
L, m	length;
L_{13}, m	nozzle mixing chamber distance;
M	Mach number;
P, Pa	pressure;
Pr	Prandtl number;
R, J/kgK	gas constant;
R_a, m	radius;
T, K	temperature;
t	turbulence intensity;
u, m/s	velocity component;
X, m	spindle coordinate.

Greek symbols

γ	heat capacity ratio;
Π	pressure ratio;
λ	velocity ratio;
ε	density ratio;
φ	friction factor;
μ, Pas	dynamic viscosity;
κ, W/mK	thermal conductivity;
ρ, kg/m^3	density;
ω, 1/s	specific dissipation rate.

Subscripts

0	total properties;
1	nozzle outlet;
2	mixing chamber inlet;
3	mixing chamber outlet;
c	critical properties;
m	mixed flow;
max	maximum;
min	minimum;
out	ejector (diffuser) outlet;
opt	optimal;
p	primary (motive) flow;
$p1$	primary fluid at nozzle outlet;
s	secondary (entrained) flow;
t	turbulence;
tot	total.

performance at critical mode. Comparison between analytical predictions and experimental data resulted in low entrainment ratio (ER) relative errors. Other studies based on this work made some additional enhancements to the previous model, (Liao [7] and Elbel & Lawrence [8]).

Antonio et al. [9] presented an integral method for design of the optimal value of mixing chamber diameter of a supersonic ejector. It included a thermodynamic model based on the 1-D isentropic flow of perfect gases with the addition of a model of losses. The model was validated with three hundred steam ejectors and showed ER relative errors less than 5%. Computational fluid dynamics (CFD) models of ejector performance for different flow geometries have also been used to validate 1-D models and predict flow performances in complicated geometries (Hemidi et al. [10]). Croquer et al. [11] compared predictions of a thermodynamic model and a CFD model. The dimensions of the ejector determined by the 1-D model