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Analytical and computational studies on the performance of a two-stage ejector–diffuser system

Fanshi Kong, H.D. Kim *

School of Mechanical Engineering, Andong National University, Andong 760-749, Republic of Korea

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ABSTRACT

The supersonic ejector–diffuser system has been extensively deployed in many industrial applications due to its exclusive advantages such as no moving parts and structural simplicity compared to other fluid machineries. However, the conventional single-stage ejector–diffuser system has been criticized for its inefficiency because of the energy loss during the mixing process and primarily, the momentum waste during the discharging process. The introduction of a two-stage ejector–diffuser system can be a useful configuration to utilize the redundant momentum of the discharged flow for improving the system performance. In the present study, the flow phenomena inside single-stage and two-stage ejector–diffuser systems have been critically predicted by means of the numerical approach using Reynolds averaged Navier–Stokes equations and the theoretical evaluation using 1D mathematical model. Both numerical and theoretical results were validated with existing experimental data. Detailed explanation and comparison has been given to detect the performance of two-stage ejector and single-stage ejector. Essential benefit coefficients obtained in the present study were specified in terms of entrainment ratio, mass flow flux ratio and the coefficient of power (COPR). Primary results of the two-stage ejector–diffuser system showed favorable capacity of collecting the extra momentum and increasing the entrainment effects of the system.

1. Introduction

The conventional single-stage ejector–diffuser (SSED) system contains a primary stream inlet, an entrained stream inlet, a mixing chamber and a diffuser. It makes use of high-pressure primary stream to propel the low-pressure entrained stream through pure shear actions without any input of mechanical energy. It has been extensively utilized for heat exchange and mass transfer in many industrial applications such as jet refrigeration system [1,2], seawater desalination system [3,4], fuel cells [5], chemical lasers [6], etc. It also has many advantages, because of the absence of moving parts, structural simplicity and little maintenance. However, its efficiency is relatively low compared with other fluid machinery. For the past decades, many researches have been made to reduce the energy loss and increase the mixing efficiency by optimizing the ejector geometries in terms of supersonic nozzle [7,8], mixing chamber [9] or additional mixing guide vanes [10]. While those optimization works are still not satisfactory due to the existing of complicated flow structures inside an ejector in aspects of mixing flow, shear layers, vortexes, shock waves and so on [11–14].

Another effective option is to introduce a second-stage ejector for better utilizing the momentum of the discharging flow at the surrounding of the first-stage ejector exit. The two-stage ejector–diffuser (TSED) system usually consists of one primary stream inlet and two entrained stream inlets, thus the second entrained stream can be propelled by the mixed flow of first-stage ejector. Giuseppe et al. [15,16] numerically investigated a two-stage ejector performance for its application in the refrigeration plant. The geometrical effects on the heat exchange were given as a function of mass flows, dimensions and temperature differences. Results revealed the increase in pressure recovery ratio over the conventional SSED system. Singhal et al. [6,17] installed a two-stage ejector for the case of dissimilar primary and entrained fluids for the application of chemical lasers, which requires extremely high pressure ratio of the ejector and high vacuum level of the entrained flow chamber. However in the practical situation of a mixing-based ejector, the entrained stream is usually open to the atmosphere thus it can be freely propelled by the primary stream. Gamisans et al. [18] studied the SSED and TSED performance for their applications in a Venturi scrubber. The installation of the second-stage ejector considerably improved the pollutant removal efficiency and the absorption efficiency of the Venturi tube.

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* Corresponding author. Tel.: +82 54 820 5622; fax: +82 54 823 5495.
E-mail address: kimhd@andong.ac.kr (H.D. Kim).

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Nomenclature

A	cross-sectional area (m^2)
c_p	specific heat (J/kg K)
D	diameter (m)
D_h	hydraulic diameter (m)
E	specific energy (J/kg)
f	friction factor
h	specific enthalpy (J/kg)
k	turbulent kinetic energy (m^2/s^2)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
M	Mach number
P	pressure (Pa)
P_{rt}	turbulent Prandtl number
R	gas constant (kJ/kg K)
Re	Reynolds number
Rm	entrainment ratio
t	time (s)
T	temperature (K)
$u_{i,j,k}$	velocity components (m/s)
$\overline{u_i'}, u_i'$	mean and fluctuating velocity components (m/s)
$\overline{u_i'u_j'}$	Reynolds-stress tensor
V	velocity (m/s)
x, y, z	Cartesian coordinates
$y+$	non-dimensional distance

Greek letters

α	benefit coefficient
γ	ratio of specific heats
δ	deflection angle (°)
δ_{ij}	Kronecker symbol
ε	roughness height (m)
θ	shock angle (°)
μ	dynamic viscosity (Pa s)
μ_{eff}	effective viscosity (kg/m s)
ρ	density (kg/m^3)
Γ_k, Γ_ω	effective diffusivity of k and ω
τ_{ij}	stress tensor
φ	mass flux (kg/m^2 s)
$\psi_{1,2,3}$	complementary coefficients
ω	specific dissipation rate (m^2/s^3)

Subscripts

1	primary stream
2	entrained stream
21	first-stage entrained stream (TSED)
22	second-stage entrained stream (TSED)
b	back pressure
c	cross-section-c
d	cross-section-d
e	exit of the ejector–diffuser system
e_1	first-stage ejector exit (TSED)
e_2	second-stage ejector exit (TSED)
i, j, k	unit vectors
m	mixing chamber
m_1	first-stage mixing chamber (TSED)
m_2	second-stage mixing chamber (TSED)
n	primary nozzle exit
o	cross-section-o
s	cross-section-s, before the normal shock wave
t	primary nozzle throat
w	cross-section-w, after the normal shock wave

Abbreviations

CFD	computational fluid dynamics
COP	coefficient of performance
COPR	coefficient of power
RANS	Reynolds averaged Navier–Stokes
SSED	single-stage ejector–diffuser system
TSED	two-stage ejector–diffuser system

Previous studies demonstrated the benefits of TSED model on the system performance in different industrial fields. The objective of present study was to improve the flow mixing and mass entrainment performance of the ejector–diffuser system by means of installing a second-stage system. Numerical and theoretical analyses were performed to design and study the TSED model, which was compared with the corresponding SSED model based on their performance. Detailed flow phenomena and benefit coefficients were investigated and predicted numerically by two-dimensional steady RANS equations through the shear-stress transport (SST) k-ω turbulence model. A new 1D mathematical model is developed to reveal the mixing process and internal flow physics of the SSED and TSED systems. The TSED model was numerically optimized to provide certain reference and basis for the design of the same type. Present CFD results and theoretical results were properly validated with experimental references.

2. Mathematical model for theoretical analysis

2.1. Assumptions and procedures

The 1D theoretical analysis of an ejector–diffuser system is to evaluate its internal flow by specifying the flow parameters along the axis using isentropic flow equations and conservation equations in terms of mass, momentum and energy. The shock wave equations were alternatively included in calculating the supersonic ejector–diffuser flow. Recently, Huang et al. [19] introduced a 1D analysis for predicting the ejector performance in terms of the entrainment ratio. Other theoretical models carried out by Zhu et al. [20,21] were consecutively developed for better evaluation of the ejector–diffuser flow. Their works assume that the velocity, pressure, density and temperature are uniform in the radial direction. However, the velocity profiles at the vicinity of ejector walls are quite non-uniform due to the viscosity effects. Their models compared with experiment results showed 10–20% errors in predicting the ejector performance [19–21]. In the present study, an updated 1D theoretical study is adopted to evaluate the ejector–diffuser flows with an acceptable accuracy. Complementary coefficients were taken into account for better prediction of the energy loss due to the flow mixing and wall frictions. Frictional and turbulent losses are considered to adapt the isentropic relations for present evaluation. Fanno flow theory expressed using an implicit Colebrook–White equation is solved by the Serghides's solution to estimate the wall friction loss inside the mixing chamber.

In the present theoretical study, the kinetic energy at the primary stream inlet, the entrained stream inlet and the exit of ejector is negligible. Inlet and outlet boundary conditions are specified by total pressures and temperatures. The working flows are treated as ideal gas. The inner wall of the ejector is assumed to be smooth and adiabatic. The working process of a SSED system is shown in Fig. 1. The high pressure primary stream (Section 1) is accelerated through a convergent-divergent nozzle, where the flow is choked at its throat (section t). The supersonic primary stream flows out