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Appraisement of Design Parameters through Fluid Dynamic Analysis in Thermal Vapor Compressor

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열 증기 압축기 내의 유동해석을 통한 설계 인자들의 영향 분석

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Key Words : *TVC(열증기압축기), Entrainment Ratio(흡입비), Compression Ratio(압축비)*

Abstract

In general, TVC(Thermal Vapor Compressor) is used to boost/compress a low pressure vapor to a higher pressure for further utilization. The one-dimensional method is simple and reasonably accurate, but cannot realize the detail as like the back flow and recirculation in the mixing chamber, viscous shear effect, and etc. In this study, the axisymmetric flow simulations have been performed to reveal the detailed flow characteristics for the various ejector shapes. The Navier-Stokes and energy equations are solved together with the continuity equation in the compressible flow fields. The standard k-ϵ model is selected for the turbulence modeling. The commercial computational fluid dynamic code FLUENT software is used for the simulation. The results contain the entrainment ratio under the various motive, suction and discharge pressure conditions. The numerical results are compared with the experimental data, and the comparison shows the good agreement. The three different flow regimes (double chocking, single chocking and back flow) have been clearly distinguished according to each boundary pressure values. Also the effects of the various shape variables (nozzle position, nozzle outlet diameter, mixing tube diameter, mixing tube converging angle, and etc.) are quantitatively discussed.

1. Introduction

TVC(Thermal Vapor Compressor) is a kind of ejector to extract and compress low-pressure fluids with high-pressure motive fluids. Its wide use in modern industry is attributed to the intrinsic features such as the high operational reliance, absence of moving parts, simple geometry, capability handling two-phase flows, and easy operation. The specific application area covers refrigeration systems, multi-effect desalination plants, and trust augmentation of V/STOL aircraft.

Most of the prior works centered on development of new applications, establishment of design procedure, experimental verification of performance, and analytic study largely restricted to one-dimensional inviscid approach. One-dimensional methods are simple and reasonably accurate, but able to treat only limited geometrical parameters. Moreover, they cannot realize the details including the repeated shock and expansion waves, the back flow to the suction chamber, recirculation in the mixing chamber, viscous shear effect, and so forth.
This supersonic mixing accompanying shock and expansion waves makes the problem significantly formidable to require an accurate two-dimensional compressible flow analysis.

Many prior theoretical approaches depended on the one-dimensional analysis. Dutton and Carroll (1983) considered an ejector for recovery of natural gas vapor from oil-storage tanks, and developed the design procedure based on a one-dimensional constant area flow model. The procedure was to minimize the motive stagnation pressure at given entrainment and compression ratios. Later, they (Dutton and Carroll, 1986) extended their previous method to optimize the entrainment and compression ratios as well as the motive stagnation pressure provided the other two variables are given. Wacholder and Dayan (1984) carried out a quantitative comparison study on the influence of various design parameters, based on the adjoint-sensitivity scheme. Since their method was basically identical to the one-dimensional constant area flow model by Dutton and Carroll (1986).

Ejectors can be classified into two branches according to the nozzle position. One with its nozzle exit located within the constant-area section is named 'a constant-area mixing ejector,' and the other with its nozzle exit located within the suction chamber 'a constant-pressure mixing ejector.' The studies for ejector started in constant-area mixing ejector. After the constant-pressure mixing ejector was known to have a better performance, it attracted many researchers' interest. Chen and Sun (1997) experimentally

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investigated the control parameters, including the operating pressures and nozzle exit Mach number for the constant-pressure mixing ejector. Riffat and Omer (2001) conducted CFD (Computational Fluid Dynamics) analysis and experimental investigation simultaneously to optimize the nozzle exit position in the converging duct. That was the first to take interest in the longitudinal shape variable. Huang *et al.* (1999) attempted one-dimensional analysis for the constant-pressure mixing ejector on the assumption that the mixing occurs inside the constant-area section. But their assumption was invalid occasionally. Because their model did not considered the shock and expansion waves in the converging duct, it inevitably required many empirical coefficients.

The objective of the present study is to appraise the effects of the various design parameters on the entrain performance of TVC. The axisymmetric flow simulation is performed, and the ideal gas law and standard k-ϵ turbulent model are employed. The details of the computational conditions and results will be presented in the following sections.

2. Numerical Simulation

Fig. 1 depicts a conventional TVC. The geometry is completely axisymmetric, and it suffices to neglect the angular dependence in a computational domain. For an axisymmetric turbulent compressible flow, the governing equations of continuity, momentum and energy are solved simultaneously with the constraint, the ideal gas law. The standard k-ϵ model is selected to model the turbulent viscosity. The solutions are obtained through the commercial CFD code, FLUENT. In this flow, the pressure difference among two inlets and one outlet is the unique driving force and determines the flow pattern. The following boundary conditions are prescribed along the respective boundaries.

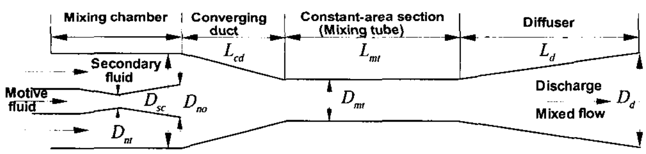

Fig. 1 Schematics of TVC.

Motive steam inlet; P_o = constant, T_O = constant (1)

Suction steam inlet; P_o = constant, T_O = constant (2)

Discharge;

P= constant, T= constant (the flow reverses to the domain) (3-a)

$\partial T/\partial \hat{n}$= 0 (the flow goes out of the domain) (3-b)

Walls; $\vec{u}$= 0, $\partial T/\partial \hat{n}$= 0 (4)

In the above boundary conditions, P, T, $\hat{n}$, and $\vec{u}$ denote the static pressure, static temperature, the outward normal vector, and the velocity vector, respectively. The subscript o, m, s, and d represent the stagnation property, motive steam, suction steam, and discharge mixture, respectively. The boundary conditions are simple, but the pressure boundary conditions applied at the inlet and outlet boundaries induces tardy convergence. The applied computational grid system is a structured mesh with about 15,000 nodes. The grid lines are stretched to place more grids near the wall for the accurate calculation. The solution is considered convergent when the sum of the residuals over the entire domain in each equation becomes less than 10^{-4}. The simulations are performed in SUN Ultra 60 workstation, and take 12 hours for each case.

3. Results and Discussions

Before getting into the parametric study for design variables, the present numerical approach is verified against the experimental data and the three different flow modes are compared with each other to help the understanding of the flow characteristics in TVC. Fig. 2 shows the simulated entrainment ratio with experimental observations of Chen and Sun (1997) for various motive and discharge pressures at a fixed suction pressure. Both studies commonly show that the entrainment ratio(the mass flow ratio of the suction to the motive) remains constant below a specific discharge pressure and decreases beyond the value. The quantitatively good agreement confirms that the present CFD analysis is sufficiently accurate in simulating the compressible mixing flow.

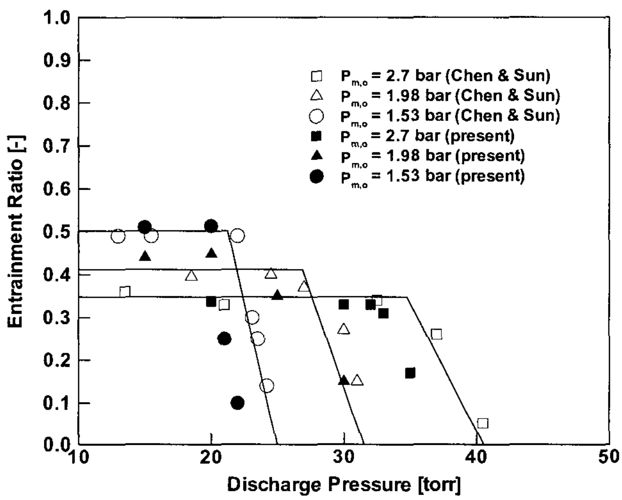

Fig. 2 Entrainment ratio with respect to discharge pressure for various motive stagnation pressure

There are three distinctive operation modes; double-choking, single-choking, and back-flow modes. In the double-choking mode both the primary and secondary flows are under the choking condition at the primary nozzle throat and the mixing tube throat, respectively. Therefore the entrainment ratio is independent of the discharge pressure provided the primary and suction pressures fix. This mode corresponds to the region of low discharge pressure in Fig. 2. Well-designed TVC always operates in the double-choking mode, and shows stable entrain performance. When the discharge pressure further increases, the entrainment decreases though the motive flow remains constant for the choking in the primary nozzle. This linearly decreasing region in Fig. 2 is the single-choking mode. At more high discharge pressure, the motive fluid flows to the suction, instead of to the discharge. This mode is called the back-flow or malfunction mode. The above test results reveal that high motive pressure increases the motive flow rate, reduces the

Table I Range of the dimensions for simulated ejector.

	Range		Range
Dnt	11 *mm*	*Lmt*	550 *mm*
Dno	20~80 *mm*	*Ld*	550 *mm*
Dmt	70~90 *mm*	*Dsc*	150 *mm*
Lcd	150~700 *mm*	*Dd*	500 *mm*

entrainment ratio, and widens the range of the useful compression ratio without back flow.

Fig. 3 (c) presents the flow structure in one of the above test cases. The motive stream shifts from subsonic to supersonic at the nozzle exit, and becomes the state of high Mach number about four with a low static pressure enough to induce the secondary fluid to enter the suction chamber. The motive fluid passes the converging duct without violent mixing with the secondary fluid. This motive stream functions hypothetically as a kind of inner wall of an annular converging duct, the secondary fluid is entrained into this hypothetical annular converging duct due to the pressure difference and viscous shear effects. The flow pattern in the converging duct is so complicated that the shock and expansion waves appear repeatedly. Also the patterns of shock and expansion waves are largely restricted to the condition of motive fluid and the shape of primary nozzle. Under the choking condition, the flow rate in converging-diverging nozzle is roughly determined by the area of nozzle throat. The passage of secondary fluid is fluted by the recurring shock and expansion waves. Therefore according to the length of converging duct, the minimum area of secondary fluid's passage is varied. From this test results, it can be predicted that the shape of converging duct will be the important design variable.

Fig. 3 (a) is the result experimentally visualized by Chen and Sun(1997). The present computation results a good agreement with experimental data and simulates well the recurring shock and expansion waves in the converging duct.

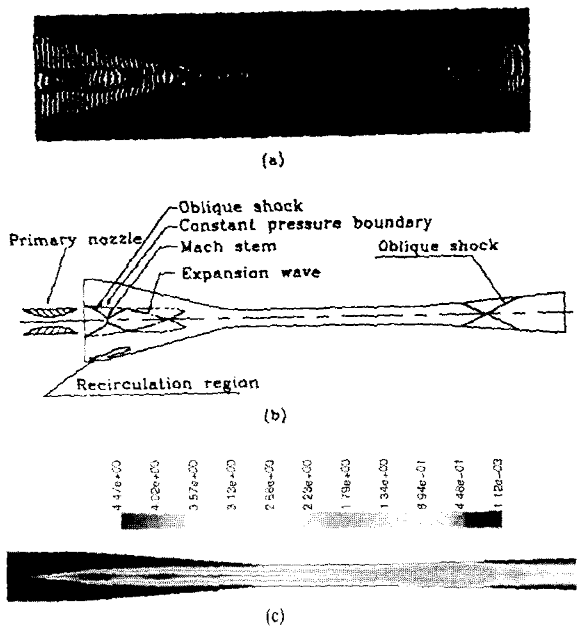

Fig. 3 (a) Holographic interferogram, Chen and Sun(1997), (b) Schematic of flow structure, (c) Iso-Mach contour, present calc.

The performance of ejector is determined by the entrainment ratio and compression ratio $(P_d/P_{s,o})$, where P_d is the static pressure at the discharge and $P_{s,o}$ the suction stagnation pressure. Depending on purpose it is necessary to maximize one of them or to optimize their combination. In this study, to maximize the quantity of sucked fluid under the fixed motive, suction and discharge pressures, and the area of primary nozzle throat, how the dimensions of shape variables affect the entrainment ratio will be investigated. Both motive and suction steams are assumed to be saturated. The stagnation pressures of motive and suction steams are constant at 8 and 0.1 bar, respectively. The discharge pressure is 0.25 bar. The tested shape variables include the primary nozzle outlet diameter (*Dno*), mixing tube diameter (*Dmt*), and the converging duct length (*Lcd*). The throat diameter of primary nozzle (*Dnt*) is an important design parameter determining the flow rate of motive steam, but its effect is excluded in this study since it is relatively well established through previous works. Table I lists the dimensional data of the simulated ejector.

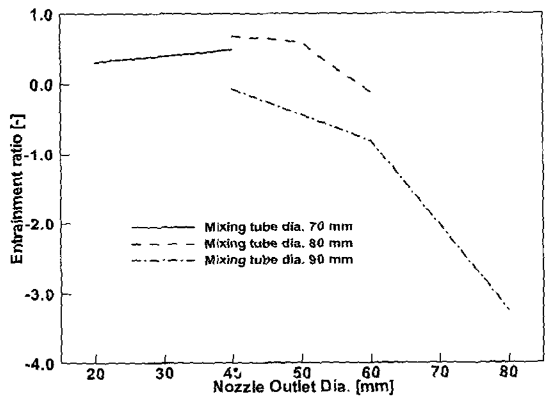

Fig. 4 Entrainment ratio with respect to nozzle outlet diameter.

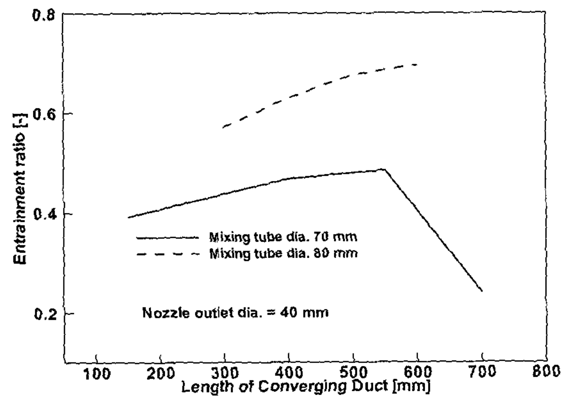

Fig. 5 Entrainment ratio with respect to converging duct length.

Fig. 4 shows the entrainment ratio with the nozzle outlet diameter and the mixing tube diameter. The trend is not monotonous; the case with mixing tube diameter 80 *mm* represents the maximum entrainment ratio. In the ejector with 90 *mm* mixing tube diameter, the back flow is detected for all the cases simulated. The entrainment ratio decreases along the nozzle outlet diameter for the cases with 80 and 90 *mm* mixing tube diameter. On the other hand, the opposite trend is observedfor 70 *mm* mixing tube diameter. This suggests that the optimal nozzle outlet diameter that achieves the maximum entraining efficiency varies with the mixing tube diameter. An excessively large mixing tube diameter removes the choking of the secondary flow. Then, the flow is subsonic and governed by the pressure difference between the suction chamber and discharge. Whether the flow is in single-choking or back-flow mode, depends on the correlation between the inertia of the secondary flow and the adverse pressure gradient.

The converging duct length has been known insignificant as a design parameter. Fig. 5, however, manifests that the length is also an important design parameter that enlarges, for some cases doubles, the entrainment ratio. This can be interpreted by the effect of converging duct on the motive-suction mixture flow. The angle of converging duct hardly modifies the primary pattern of motive steam, but has significant influence on the area of hypothetical throat, consequently the entrainment property. Consequently, an ejector has the optimal converging duct length with respect to the mixing tube diameter.

4. Conclusions

The CFD analysis was performed for the supersonic flow in the constant-pressure mixing ejector. Given the motive and suction pressures, the discharge pressure determined three typical operation modes of double-choking, single-chocking, and back-flow modes. The internal flow structures for two latter abnormal modes were also clearly disclosed. Simulations with various dimensional variables including the mixing tube diameter, primary nozzle exit diameter, and the converging duct length revealed that even trivial parameters such as the converging duct length significantly affected the entrainment ratio. There exist the optimum values to maximize the entrainment for all tested design variables.

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