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공동을 이용한 초음속-아음속 평행류에서의 혼합증대에 관한 수치적 연구

문성목* · 장세명** · 김종암*** · 이경훈* · 김인수* · 안수홍* · 우관제*

Numerical Study on the Mixing Enhancement of Parallel Supersonic-subsonic Wakes Using Wall Cavities

Moon, Seong-Mok* · Chang, Se-Myong** · Kim, Chongam*** · Lee, Kyoung-Hoon* · Kim, In-Soo* · Ahn, Su-Hong* · Woo, Kwan-Je*

ABSTRACT

A computational study on the enhancement of parallel supersonic-subsonic mixing wakes is conducted and compared with available experimental data. The first aim of the present work is to show a direct comparison between numerical predictions and equivalent experimental data for the baseline case. The Pitot pressure distribution data are in good agreement between computation and experiment, and the results show that Menter's SST model with the compressibility correction gives the best performance. Further we investigate the effects of primary parameters such as the position of the cavity, and the arrangement of the cavity at the given flow condition.

초 록

평행 초음속-아음속 후류유동에서 혼합증대에 관한 수치적인 연구를 실험결과와의 비교를 통하여 수행하였다. 이번 연구의 첫 번째 목적은 실험에서 사용된 조건으로 정확하게 수치적으로 모사하는데 있다. Pitot 압력을 이용하여 수치계산결과와 실험치와 비교하였을 때 서로 일치된 결과를 얻었으며, 그 중에서 압축성 수정을 가미한 $k-\omega$ SST 난류모델의 계산결과가 가장 좋은 것으로 나타났다. 게다가 기존의 유동조건에서 공동의 위치, 배열수에 변화를 주면서 혼합특성을 비교/연구하였다.

Key Words: Parallel Supersonic-subsonic Wake(평행 초음속-아음속 후류), Mixing Enhancement(혼합증대), Acoustic Wave(음향파), Wall Cavity(벽면 공동)

1. Introduction

In the design of scramjet engines, the mixing problem of fuel and oxidizer has been an interesting issue in the engineering, and many technical articles have been published, including various ideas for enhancing the mixing rate[1]. Among the methods for fuel-air mixing

* 현대로템 응용기술연구팀
** 군산대학교 기계자동차공학부
*** 서울대학교 기계항공공학부
연락저자, E-mail: seongmmoon@hyundai-rotem.co.kr

enhancement[2,3], Sato et al.[3] performed a preliminary experiment on the mixing enhancement of parallel supersonic-subsonic wakes with irradiation of acoustic waves emitted from a wall-mounted cavity in the supersonic flow field. They illustrated that the mixing was enhanced by the acoustic disturbance, and the mixing rate was controlled with the cavity shape while the total pressure losses were negligibly small.

Figure 1 shows a typical schematic pattern of parallel supersonic-subsonic mixing flow. The subsonic flow ($M_2 = 0.3$) is injected into the uniform supersonic flow ($M_1 = 1.78$) through a parallel 2-D nozzle, retaining its speed before a length of X_c from the nozzle exit. Such parallel supersonic-subsonic flow is surrounded with highly turbulent shear layers, and interactions between the acoustic waves and this shear layer produce complex turbulent shear flow. Few numerical studies on this problem have been reported in the literature because of the complexity of turbulence. The current article is aimed first at presenting a direct comparison of numerical predictions with experimental results by Sato et al.[3], so we reproduce their experimental model numerically through the adoption of turbulence models with the compressibility correction. Finally we study the effect of parameters such as the position of the wall cavity and the arrangement of the cavity in which the parameters are varied from the baseline case to find the optimal condition which enhances the mixing of parallel supersonic-subsonic wakes.

2. Numerical Methods

Two-dimensional, time-dependent, Reynolds-averaged compressible Navier-Stokes equations (RANS) as the governing equations are used. The inviscid flux vector is discretized with the finite-volume flux difference method based on the Roe's approximate Riemann solver. A monotonic upstream-centered scheme for conservation laws (MUSCL) interpolation is applied to obtain the third-order extension of spatial accuracy. For the temporal integration, the lower-upper symmetric Gauss-Seidel algorithm is combined with the dual time-stepping technique[4] of second-order temporal accuracy. The turbulence models[5] chosen for this study include six EVMs (the Spalart-Allmaras model, the standard $k-\epsilon$ model, the RNG $k-\epsilon$ model, the realizable $k-\epsilon$ model, Wilcox's 1998 model, Menter's SST model) and two RSM models (the LRR model, Wilcox's stress-ω model).

3. Results and Discussion

3.1 Analysis and Comparison with Experiment

3.1.1 Configuration and Computational Conditions

As shown in Fig. 1, the computational domain consists of a block (120mm×40mm) which is equivalent to the experimental setup of Sato et al.[3]. The subsonic flow (flow 1 in table 1) is injected into the supersonic base flow (flow 2 in table 1) through a rectangular nozzle in a 2-D manner. All of the flow conditions[3] are shown in the Table 1. The Reynolds number based on the height of injector is 3.16×10^5.

3.1.2 Comparison of the CFD Results with Experimental Data

The computational grid system of approximately 120,000 nodes is used for the treatment of acoustic wave propagation. Figures 2 and 3 show the computational results for noncavity and cavity cases. The expansion wave at the sharp edge from the rectangular wall and the recompression wave due to the expanding

Table 1. Computational Conditions

	M	$u(m/s)$	$T_0(K)$	$P(N/m^2)$
Flow 1	1.78	473	288	1.013×10^5
Flow 2	0.3	100	288	1.013×10^5

parallel jet are observed in the computational results for both cases. The Pitot pressure distributions along cross sections at the developing region of the free-wake turbulent jet are measured as shown in Figs. 4 and 5 to compare with data in [3]. Good agreement between the present computational results and Sato's experimental data is shown. As shown in Figs. 4 and 5, the dynamic pressure of the subsonic jet (or minimum Pitot pressures at $x/H=0$) is higher if there is forcing of acoustic waves generated from the wall-mounted cavity, so proper acoustic waves propagated from the wall increase the mixing rate of the parallel supersonic-subsonic wakes.

The prediction by Menter's SST model reproduces the characteristic features of the Pitot pressure distributions better than the other models. Thereupon, Menter's SST turbulence closure model is chosen for the parametric study.

3.2 Parametric Studies

The parametric study of mixing enhancement using an acoustic wave generator, or a cavity, is conducted to ascertain the effect of position (X_p in Fig. 1) and cavity number. The computational condition ($X_p=18.2mm$; one cavity) for comparisons with the experimental data in the previous section is selected as a baseline case.

3.2.1 Effect of Cavity Position

The effect of change of cavity position X_p is investigated. Figure 6(a) shows the existence of optimal position near $X_p=15.2mm$ for better mixing enhancement. The minimum Pitot pressure at $X_p=15.2mm$ is slightly higher than that for the baseline case, so the mixing rate is improved for this case over baseline.

3.2.2 Effect of Cavity Number

Effects of the number of cavities are examined. As illustrated in Fig. 6(b), the staggered three-cavity configuration best mixes the parallel flows because the asymmetry activates flow instability inside the shear layer. The symmetric configuration does not have a noticeable effect on the mixing enhancement.

4. Concluding Remarks

A computational study on the enhancement of parallel supersonic-subsonic mixing wakes, which models the fuel injection system in the combustor of a scramjet engine, has been conducted using a finite-volume-based RANS solver. The present study is aimed mainly at finding a proper numerical method for simulating complex turbulent flow involving the free shear layer, jets, and wakes. The eight turbulence models were tested thoroughly, including six EVMs and two RSMs. The computational results are in good agreement with equivalent experimental data for Menter's SST model.

The parametric study was done to provide improvement of mixing enhancement over the baseline case. Two main parameters were considered in this study: the position and the arrangement of cavity. Once the incidence of acoustic wave propagating from the wall cavity locates fully inside the mixing region, no significant difference can be found. The staggered cavity configuration can improve the mixing rate because it gives flow more instability, which may bring about better enhancement of turbulence mixing.

Acknowledgment

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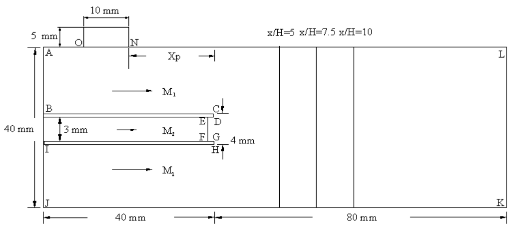


Fig. 1 Mixing problem of parallel supersonic-subsonic wake

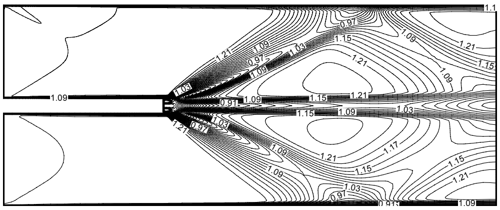


Fig. 2 Density contours at a given instant without a cavity [kg/m^3]

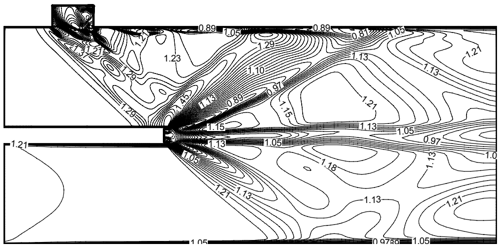
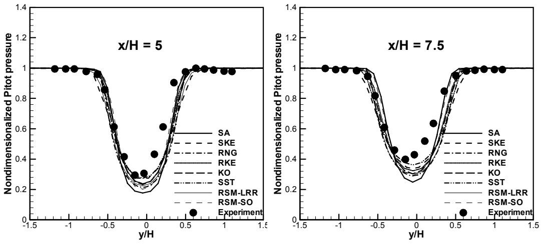
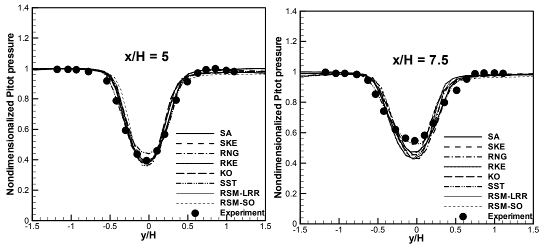


Fig. 3 Density contours at a given instant with a cavity [kg/m^3]



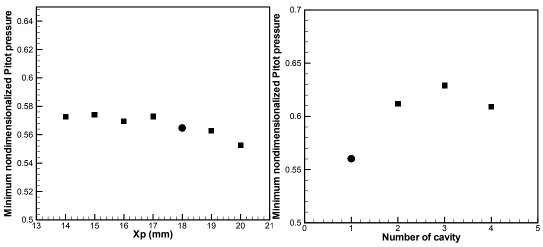
(a) x/H = 5 (b) x/H = 7.5

Fig. 4 Nondimensionalized Pitot pressure distributions (without a cavity)



(a) x/H = 5 (b) x/H = 7.5

Fig. 5 Nondimensionalized Pitot pressure distributions (with a cavity)



(a) Effect of cavity position (b) Effect of cavity number

Fig. 6 Minimum nondimensionalized Pitot pressure distributions (● baseline case)