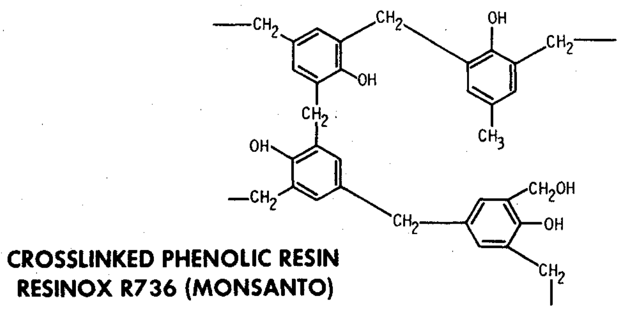

Fig. 2 Chemical structure of phenolic resin copolymer unit.

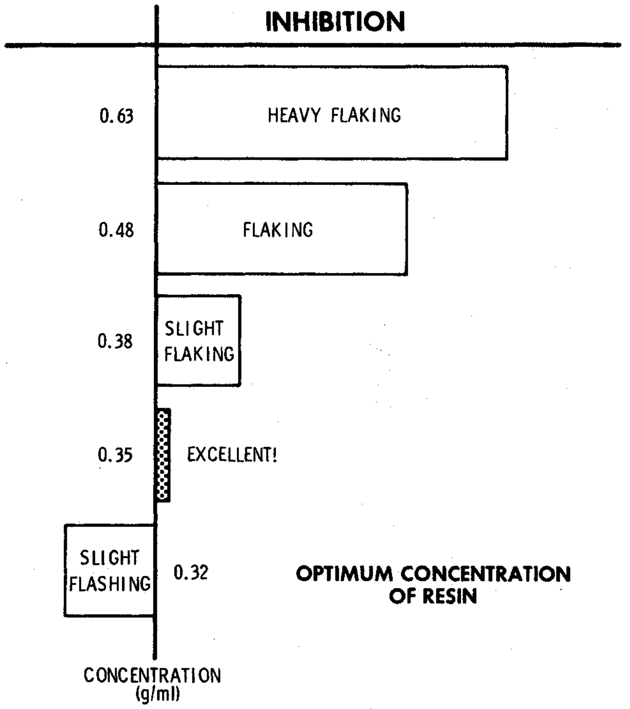

Fig. 3 Qualitative behavior of polymer inhibitor vs solution concentration.

agents for enhancing flexibility are clean-burning cellulose fibers or various rubber-based compounds. The present formulation was developed for work at low (50-200 psi) pressures. Formulations for work at higher (300-1000 psi) pressures can easily be developed.

Acknowledgments

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Gradual Opening of Skewed Passages in Wave Rotors

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Introduction

THE problem of gradual opening of rectangular axial passages in wave rotors was studied in Ref. 1. In that reference, the mathematical model used to simulate the opening process was decribed in detail. This Note is intended as an extention of the previous article.

Historically, most wave machines designed to produce shaft power had skewed passage.[2,3] For this reason opening of a skewed passage is analyzed in this paper, and conclusions drawn for the case of rectangular axial passages are examined in light of the results for the skewed case.

Results and Discussion

The main conclusion of the study on the gradual opening of the rectangular passage is that in order to minimize the mixing losses caused by rotational flow in the passage, opening of the wave rotor passage will lead to a one dimensional flow pattern in the passage which will in turn lead to minimal mixing losses.

When the passage of the wave rotor is skewed, even an instantaneous opening of the passage will not lead to the development of a one dimensional flow pattern with small losses.

As an example, the opening process for a passage 0.02 m wide and 0.24 m long is modeled. The passage has left and right hand inlets parallel to the Y axis and the upper and lower wall of the passage form a 60 deg angle with the positive direction X axis. It is assumed that initially air in the passage is at the following conditions:

$$P_0 = 1\ \text{atm}; \quad \rho_0 = 1.2\ \text{kg/m}^3; \quad U_0 = 0; \quad V_0 = 0$$

The driver gas entering through the port at the left hand end is assumed to having the following properties:

$$P_d = 1.8\ \text{atm};\ \rho_d = 1.81\ \text{kg/m}^3;\ U_d = 75\ \text{m/s};\ V_d = 129.9\ \text{m/s}$$

The conditions for the driver and driven gas are the same as those assumed for the case of the rectangular passage as reported in the Ref. 1.

Figures 1a and b illustrate results obtained from the simulation of the instantaneous opening of the skewed passage in the form of pressure and velocity contours at a sequence of times. The flow pattern near the inlet in Fig. 1 is highly rotational which suggests very high mixing losses. This pattern arises partially because of the reorientation of the shock wave. In the first moments following the opening of the passage, the shock wave between the driven and driver gases is oblique to the lower and upper walls of the passage. At later times, this shock wave turns and becomes normal to the upper and lower walls. Thus, for skewed geometry passages there is no obvious condition for minimizing the mixing losses caused by the inlet opening.

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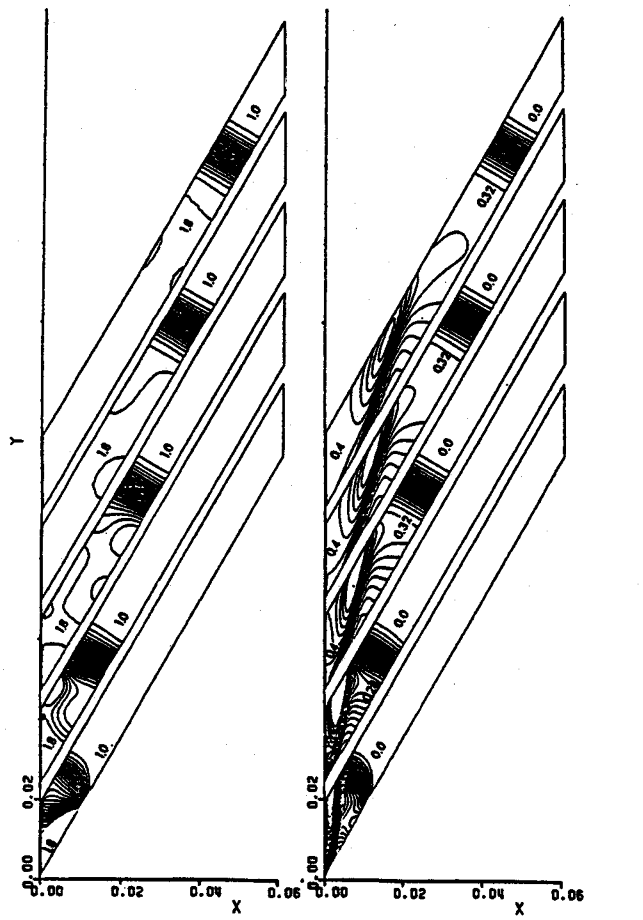
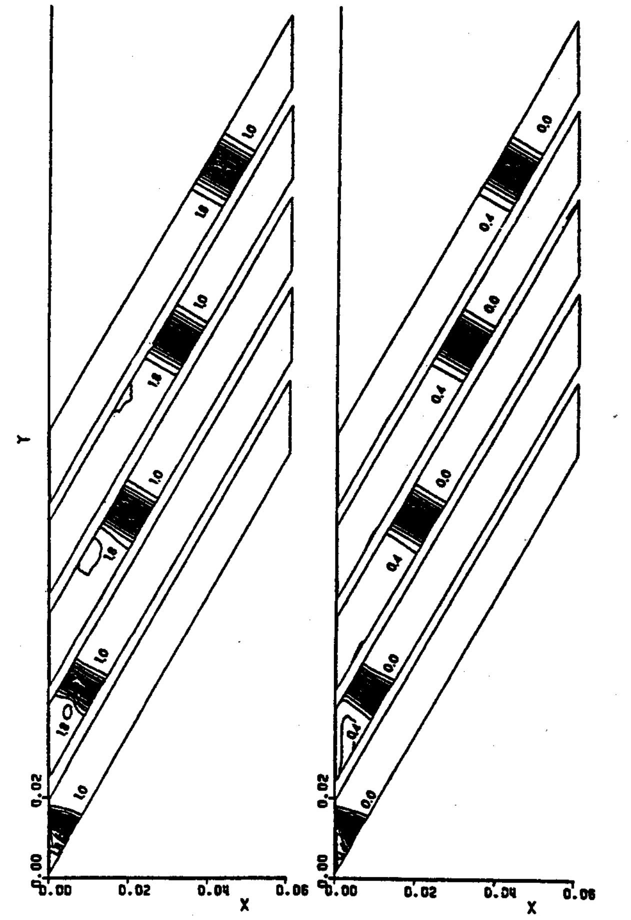


a) Pressure contours. b) Mach number contours.

Fig. 1 The flow pattern evolution after instantaneous opening of the 60 deg skewed passage. Time is along the Y axis (not to scale).



a) Pressure contours. b) Mach number contours.

Fig. 2 The flow pattern evolution for the passage gradual opening with the velocity according to $V_{open} = V_{SH}/\sin\alpha_{SK}$. Time is along the Y axis (not to scale).

It would seem reasonable to postulate, however, that if a shock wave could be formed which would be at all times normal to the lower and upper passage walls, then the rotational flow and mixing will be minimal.

Study of the formation of the shock wave front at the inlet led to the conclusion that for the shock wave forming at the inlet to remain normal to the lower wall, the inlet should be opened at the rate

$$V_{op} = V_{sh}/\sin\alpha_{sk} \tag{1}$$

were V_{op} is the velocity of the inlet opening, V_{sh} the shock wave velocity in the media; and α_{sk} the angle of the skewed passage. The V_{op} velocity is equal to the velocity with which the shock wave surface will slide along the inlet wall.

In Figs. 2a and b, results for the modeling of the gradual opening of the skewed passage inlet with the opening velocity described as in Eq. (1) are shown. It is apparent from Fig. 2a and b that for this case the shock wave surface remains virtually normal to the walls of the passage, which will lead to near minimum mixing losses.

Conclusion

Modeling of the gradual opening of skewed passages revealed a method of reducing mixing losses at the passage inlets. The mixing will be minimal when the velocity of the opening is matched with the shock wave velocity in the passage divided by the angle of skewed passage. Our simulations show that even when conditions for the optimal opening are not completely satisfied, reduction of the rotational losses could be significant if the opening velocity is ±15% of the optimal value.

It can be concluded that a very high opening velocity is required in order to obtain low mixing loss. The opening velocity of the passage should be always higher than the velocity of the shock wave generated in the wave rotor passage at the driver gas inlet. Even substantially skewed passages with $\alpha_{sk} = 65$ deg will require according to Eq. (1) the opening speed to be approximately 10% higher than the shock wave velocity in the passage and that is not easy to achieve for the typical flow conditions in the wave rotor.

Another limitation is that even when this optimal speed of opening is achieved at one port, the speed of opening will not be optimal at the other ports where the flow conditions would be different (i.e. driver gas inlet optimal speed will be different for that of the driven gas outlet). Thus, proposed method for reduction of mixing losses should be integrated with other design considerations. However, from our study one can conclude that mixing losses in skewed passages will be smaller than in the rectangular passages, if the gradual opening of the skewed passage begins from its acute angle and all other conditions are the same. The reason for this is that skewed passage shock wave developing in the passage should turn on a smaller angle in order to become normal to the walls of the passage.

Acknowledgment

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Real Gas Effects on the Numerical Simulation of a Hypersonic Inlet

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Introduction

THE aerodynamic performance of the air-induction system is an important factor in establishing the viability of a hypersonic vehicle design. Since the inlet performance is primarily a function of the internal contour geometry, the development and assessment of analytical techniques for the design of internal contours are items of primary concern. The inlet design technology must have a detailed and accurate flowfield calculation procedure that includes the effect of the boundary layer. Although a full Navier-Stokes procedure provides the necessary generality to predict the flow in an inlet, the required computer time and storage indicate that such a procedure should be used only if no suitable alternative exists.[1] An optimum analysis possesses the general viscous nature of the Navier-Stokes equations, but takes advantage of realistic physical approximations to limit the computer running time and storage requirements associated with the solution of the complete Navier-Stokes equations. One approach is to use a spatial-marching procedure, which reduces the complete Navier-Stokes equations to a form that can be treated as an initial boundary value problem and solved by forward marching in space. The assumption made is that a primary flow direction exists and that diffusion in this direction can be neglected. In this manner, a set of steady-state equations is produced for entirely supersonic flows that can be solved by an efficient spatial-marching procedure. In any embedded subsonic regions, such as at no-slip walls, further approximations are required to allow solution by spatial marching.

Description of Problem

Hypersonic Inlet

The problem considered is the numerical simulation of the flowfield in a two-dimensional, high-speed inlet. The geometry of the inlet is shown in Fig. 1. The model exhibits the significant characteristics of hypersonic inlets, for which extensive experimental data have been documented.[2] The model, denoted as P8, represents inlet configurations typical of cruise condition of a hypersonic airbreathing vehicle. It was designed to provide an internal compression ratio of 8. The forebody wedge is a nominal 6.5 deg, intended to match a design Mach number of 6 at the inlet entrance under the test conditions of a freestream Mach number of 7.4, allowing for boundary-layer displacement effects. The wedge was cooled, providing a relatively uniform surface temperature of 0.375 $T_{t\infty}$, where the freestream total temperature $T_{t\infty}$ is 811 K. The freestream Reynolds number is 8.86×10^6 m^{-1}. The boundary-layer transition point was found experimentally to be at approximately 40% of the distance between the wedge leading edge and the inlet entrance.

The cowl was designed with a leading-edge diameter of 0.114 cm and the cowl was kept at constant temperature of 0.375 $T_{t\infty}$. For the P8 inlet, the cowl boundary-layer transitions are located approximately halfway between the cowl leading edge and the throat station.

The inlet configuration, with realistic geometry, important viscous-inviscid interactions, and extensive experimental data, provides an excellent opportunity to verify the efficacy of the numerical method and to understand the complex phenomena of high-speed inlets.

Real-Gas Effects

At hypersonic speed, temperature changes across the shock wave can be so high that the imperfect-gas effects become important. The gas can be considered to be thermally perfect (i.e., $Pv=RT$), but calorically imperfect (i.e., specific heats are not constant, but a function of temperature). The effect of variable specific heats can be illustrated in Fig. 2, in which the total pressure ratio across a normal shock wave is plotted against the Mach number for three different values of the ratio of specific heats, corresponding to upstream static temperature of 500, 1000, and 1500 R. It can be seen that if the normal shock occurs at a Mach number of 5, the difference in total pressure loss across the shock is more than 20% for $\gamma=1.4$ (500 R) and

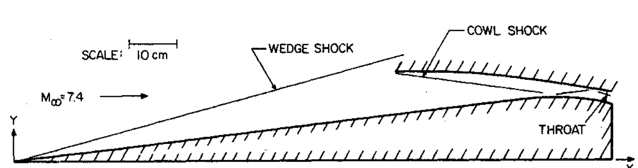

Fig. 1 Hypersonic inlet geometry.

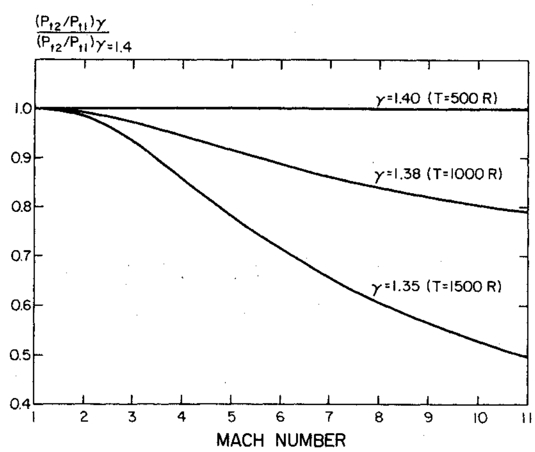

Fig. 2 Effect of caloric imperfections on the total pressure across a normal shock wave.

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