The Problem of Gradual Opening in Wave Rotor Passages

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The influence on the flow pattern of the gradual passage opening in the wave rotor is studied on the basis of numerical simulation. It is found that, in most cases, significant volume of the passage will have rotational flow, which should lead to the mixing between the driver and driven gases. In some cases, losses will occur also as a result of the multiple reflection of the shock and pressure waves from the passage walls. It is shown that the interface between driven and driver gas will be oblique to the passage walls, when the passage opens gradually, and the interface can retain its obliqueness to the walls.

Introduction

WAVE rotors are devices that use wave propagation through the fluid in a rotor passage to transfer energy from one fluid to another[1] or to transfer energy from one fluid to rotor shaft and another fluid.[2] Wave rotors, wave engines, wave pressure exchangers, wave equalizers, and Comprex[1] are all based on the same idea of energy exchange in the unsteady waves, and the topic of the present study is relevant to all of these devices.

Wave rotors offer the potential for significant improvements in air-breathing engine propulsion cycles because they can be self-cooling, since both high-pressure gas and cold low-pressure gas use the same passage for alternate periods of time in the cycle. Combining a wave rotor with conventional turbomachinery components shows promise of significant reduction in specific fuel consumption without weight or size penalties.

The principles of operation of wave rotor devices and their commerical applications can be found in Refs. 1-3. For completeness, the general scheme of a wave pressure exchanger will be described, as illustrated in Fig. 1. One gas (driver) at high pressure is used to compress a second gas (driven). The process is arranged to occur in tube-like passages with trapezoidal cross section located on the periphery of a rotating drum or rotor. The compression is achieved successively in each rotor passage by means of compression waves or shock waves generated by the entering driver gas. The compressed driven gas is drawn off from the end of the passage when it aligns with an outlet port. The driver gas then undergoes a series of expansions to a lower pressure and is scavenged out by freshly inducted driven gas at approximately the same pressure level. This fresh "charge" is then compressed by the high-pressure driver gas and the cycle repeats itself. Steady rotation of the drum sequences the ends of the passages past stationary inlet ports, outlet ports, and endwalls. This establishes unsteady but periodic flow processes within the rotating passages and essentially steady flow in the inlet and outlet ports. The passage may be oriented axially as in Fig. 1 or at a stagger angle. In general, wave machines used as pure pressure exchangers (e.g., "Comprex"[1]) have usually axially oriented passages, while those with staggered passages may drive a shaft, since shaft work extraction is possible with this latter configuration.

In the design of the wave rotor, it is very desirable to determine the optimal ratio between the width and length of the single passage of the rotor. Usually only two parameters are evaluated to determine this ratio: skin friction losses and bypass losses. The number of passages on the rotor should be minimal to minimize skin friction losses. On the other hand, the passage should be narrow compared to the port widths to reduce flow bypass between inlet or outlet ports. The transient process of the passage opening or closing (as the passage end moves across a port or moves from a port to be closed by the endwall, respectively) usually is not considered in the design. It is generally assumed that the passage opening or closure occurs instantaneously.

Pearson[2] tried to take into account the gradual opening of the passage, assuming that the air in the passage is compressed in a series (usually three) of discrete compression waves which converge and ultimately merge to form a shock wave. This allowed him to design a complicated wave machine cycle for a rotor using relatively short passages. However, since the technique was one-dimensional it could not reveal the peculiarities of this essentially two-dimensional flow and would be valid only for very weak waves.

In the present study, by means of numerical modeling, we will examine in real-time how the gradual opening influences the wave formation in the wave rotor passages and how that should affect the rotor design.

Model

The assumptions involved in the numerical simulations are described as follows.

The flow in each passage of the wave rotor is unsteady and periodic. At the same time, the flow through the ports is (ideally) steady.[1,2] The peripheral width of the port is usually equal to several widths of a single passage, and herein it is assumed that the flow in the inlet or outlet port remains stationary when the passage-end encounters the port. For this reason the region of the port is not included in the computational domain shown in Fig. 2.

The time-dependent process of the passage-end translating across the region of the inlet or outlet port will be referred as the "gradual opening" of the passage. The passage opening process will be referred as "instantaneous," when the assumption is made that the passage instantaneously opens to the port area and is subjected immediately to the steady flow conditions at the port.

It is assumed that the flow is inviscid and can be modeled by the Euler equations. The unsteady two-dimensional Euler equations can be written in conservation law form as

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial X}+\frac{\partial G}{\partial Y}=0$$

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where

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ e\end{bmatrix}\quad F=\begin{bmatrix}\rho u\\ p+\rho u^2\\ \rho uv\\ (e+p)u\end{bmatrix}\quad G=\begin{bmatrix}\rho v\\ \rho uv\\ p+\rho v^2\\ (e+p)v\end{bmatrix} \tag{1}$$

Here ρ is the density, u and v the velocity components in the X and Y coordinate directions, p the pressure, and γ the ratio of specific heats. The energy per unit of volume, e, is defined by

$$e=\rho\left(\epsilon+\frac{u^2+v^2}{2}\right)$$

where $\epsilon=P/(\gamma-1)\rho$ is the internal energy. We look for the solution of the system of equations represented by Eq. (1) in the computational domain shown in Fig. 2 in time t with the following conditions at the domain boundaries: a) solid wall along segments 1-3 and 2-4, b) outflow along segment 3-4, and c) inlet along segment 1-2.

It is assumed that initially at time $t=0$, the passage of the wave rotor is filled with stationary gas at ambient conditions. When instantaneous opening of the wave rotor passage was simulated, it was assumed that at time $t=0$, the flow at the inlet 1-2 was equal to the steady flow in the port. When gradual opening of the passage was simulated, at time $t=0$, the inlet was closed and solid wall boundary conditions were imposed at the inlet 1-2. Then, this boundary condition was gradually replaced by the flow condition at the inlet port. The length uncovered to the inlet port region, where the solid wall boundary conditions were replaced by the inlet port conditions, was determined using the elapsed time and the velocity of the passage relative to the inlet port.

The Godunov method was used to obtain a numerical solution of Eq. (1) with the described boundary and initial conditions. Details of the implementation of the method and boundary conditions are given in Ref. 4.

The flowfield was modeled for the rectangular passage with a width of 0.02 m and a length of 0.12 m. The grid covering the computational domain of the passage is shown in Fig. 2.

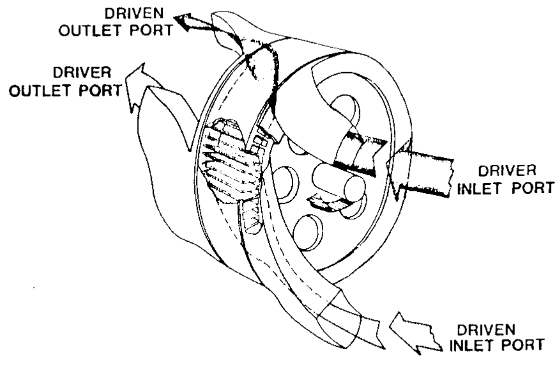


Fig. 1 Wave rotor operation scheme.

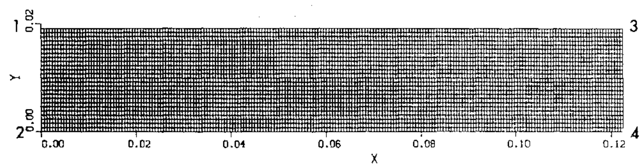


Fig. 2 Computational domain.

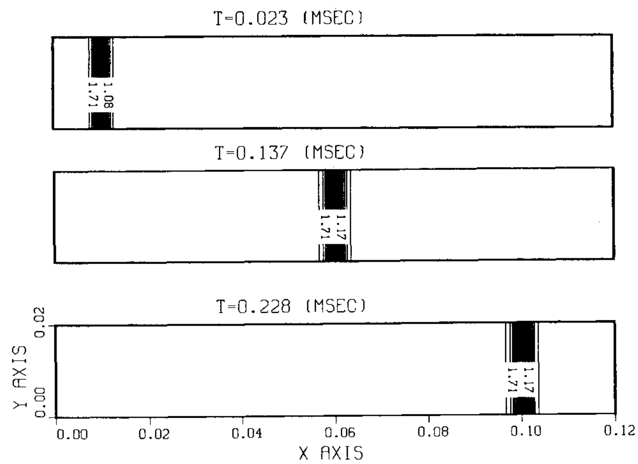


Fig. 3 Evolution in time of the shock wave formed after instantaneous passage opening.

Results and Discussion

The following initial conditions were assumed for the air initially in the passage:

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

The driver gas entering through the port at the left-hand end was assumed to have the following properties:

$$P_d=1.8\ \text{atm}\quad \rho_d=1.81\ \text{kg/m}^3\quad U_d=150\ \text{m/s}\quad V_d=0$$

These conditions correspond to a practical situation in a wave rotor when a passage filled with a quiescent fresh charge of air at ambient conditions encounters an inlet port supplying hot, high-pressure driver gas.

If the assumption is made that the passage instantaneously opens and is subjected to the conditions of the inlet flow at the left boundary 1-2 (see Fig. 2), then a perfectly one-dimensional flow pattern should develop in the passage. The results of the modeling of these conditions are presented in the form of pressure contours at progressively larger time steps in Fig. 3. Time $t=0$ corresponds to the moment when the passage opens. Instantaneous opening of the passage is seen in Fig. 3 to lead to an immediate formation of a shock wave and subsequent propagation in the passage from the left to the right. The flow conditions at the inlet port are matched to the parameters of the rarefaction wave which effectively will cancel the rarefaction wave moving toward the inlet at the left end of the passage. For this reason the flow in the passage has no additional discontinuity. This situation is typical for a wave rotor, where flow conditions at the ports are chosen in such a way that waves do not propagate from the passages into inlet or outlet ports. The flow in the ports will therefore remain steady. In the case shown in Fig. 3, the shock wave was found to propagate with a velocity, $V_{sh}=446$ m/s, the interface with a velocity $V_{in}=150$ m/s, and all the parameters examined were confirmed accurately using one-dimensional gasdynamics relationships.

Most of the approaches used in wave rotor design are based on the assumption that the waves are one-dimensional in nature. When the gas is compressed by a weak shock wave, for instance, assumptions are made that, 1) the process is isoentropic, 2) the hot and cold gases are strictly separated by a planar interface, and 3) the flow is everywhere irrotational. This leads to the very high efficiencies projected for the compression. If the passage is wide enough so that viscous effects can be neglected, this model of the compression in the wave rotor passage is realistic, but only for instantaneous passage opening or for a very long passage. Results presented below illustrate how the gradual passage opening affects the compression process.

In Fig. 4, the pressure and Mach number contours in the passage are shown at a sequence of times for the case of a gradual opening to the inlet port with a velocity of 100 m/s. Parameters for the gas in the passage, before opening begins, and in the inlet port are the same as for the case of instantaneous opening. The dynamics of the flow development seen in Fig. 4a is very different from that shown in Fig. 3. First, curved pressure waves radiate from the initial small opening appearing at the lower corner of the inlet on the left side of the passage ($t=0.044$ ms in Fig. 4). Subsequently, these waves reflect from the upper wall of the passage and at time $t=0.125$ ms have formed a row of compression waves which have approximately straight fronts normal to the wall of the passage. Initially, compression waves of this kind occupy a small part of the region with disturbed gas. In the region well behind the front of this quasi-one-dimensional propagation, compression waves are curved and are the result of the interaction between the waves reflecting back and forth between the lower and upper walls of the passage and the new waves created by the progressive opening of the port to the passage. Since it is possible to see in Fig. 4 for the times $t=0.084$ and 0.166 ms, respectively, the flow behind the quasi-one-dimensional region is highly rotational and is relatively constant pressure in the X direction. The passage became fully opened only at $t=0.2$ ms. At this time compression waves are propagating along the length of the passage and the pressure rises gradually from 1 atm at the right end to 1.8 atm at the left end. The front of converging compression waves will eventually become a shock wave, but this will occur at some later time and outside the computational domain.

It was concluded from the case presented in Fig. 4 that a passage length-to-width ratio of 6 will lead to very high mixing losses and nonuniform and inefficient compression, since in this case the region of rotational flow occupies half of the passage volume. Additional losses will be produced because of the highly rotational flow within each of the two gases.

In Fig. 5, pressure and velocity contours are shown for the case of gradual opening of the passage with a velocity of 200 m/s. Full opening of the passage in this case occurred at $t=0.1$ ms. A curved shock wave is formed at $t=0.044$ ms. This shock wave (see Fig. 5a) partially reflects from the upper wall of the passage and then, gradually converging with its main front, forms an almost planar shock front at the time $t=0.252$ ms. However, even then the flow is highly rotational behind the shock front, and the region of rotational flow occupies one-third of the passage volume. In this region the gas velocity increases from $M=0.3$ at the upper wall to $M=0.52$ at the lower wall.

When the velocity of the passage opening is increased to 500 m/s (see Fig. 6) the passage becomes fully open at $t=0.04$ ms. Because of the fast opening of the passage, the shock wave at the time $t=0.04$ ms is less curved and only a small fraction of the shock front reflects from the upper wall. This reflected part of the shock front converges with the main front at $t=0.172$ ms. From that time on, the flow pattern in the passage is mostly one-dimensional with a small and weakening region of rotational flow behind the main front. Nevertheless, even for this case, with passage length/passage width = 3, there will be very high mixing losses, with a large part of the passage volume subjected to rotational flow.

In order to study how the strength of the shock wave influences the flow pattern developing in the passage, an additional case was simulated where the parameters of the driver gas at the inlet port area were increased; namely, to

$$P_d=2.85 \text{ atm} \quad U_d=283 \text{ m/s} \quad \rho_d=4 \text{ kg/m}^3$$

As in the previous case, the parameters of the driver gas were chosen in such a way that waves do not propagate back into the port when the passage opens. Results of this simulation

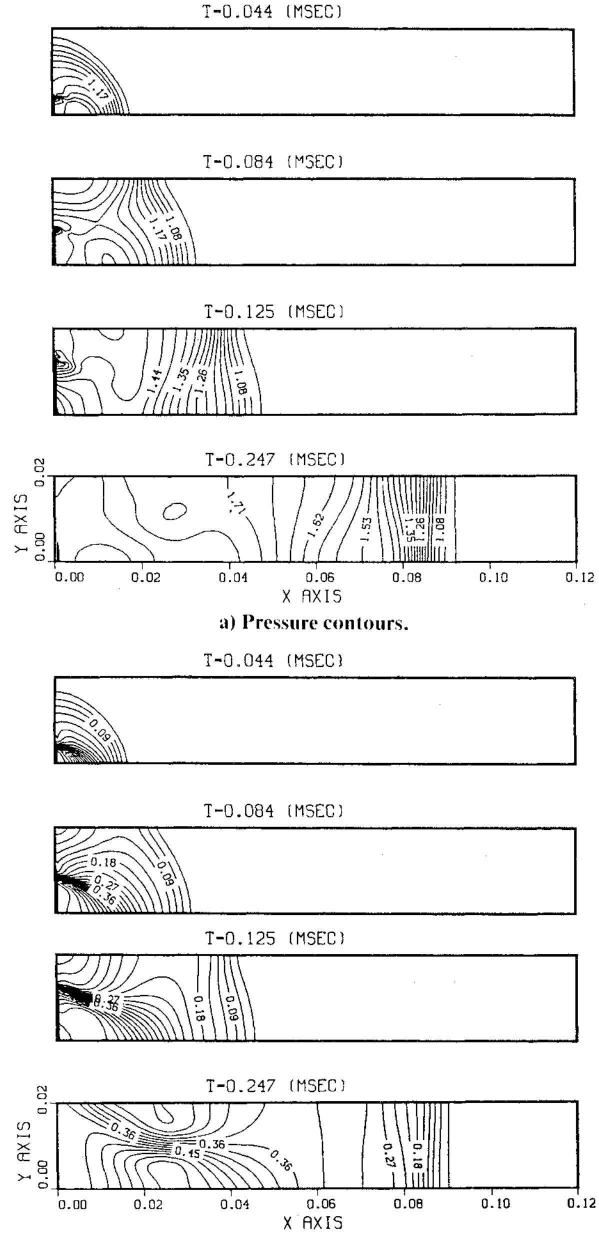
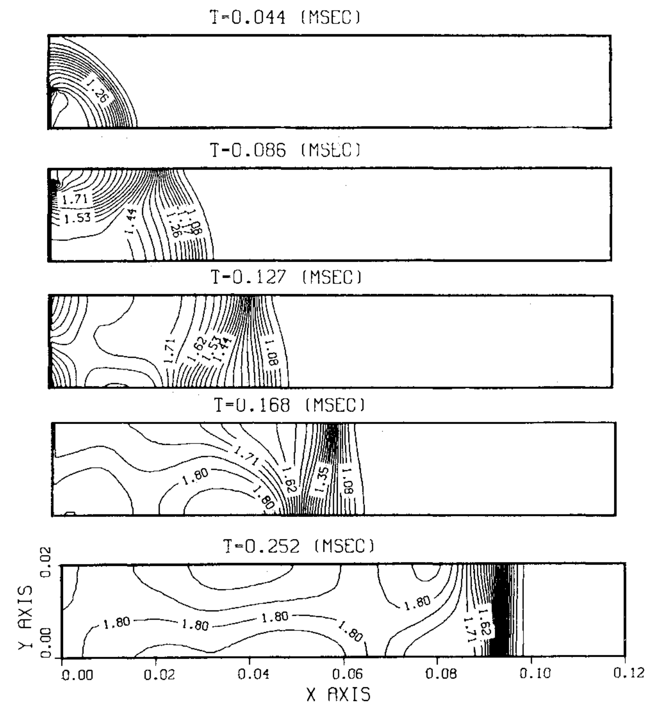


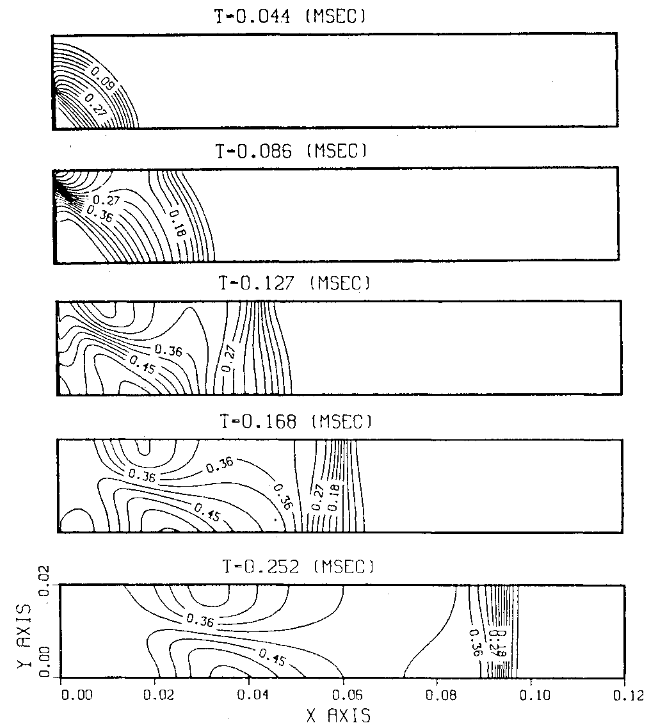
Fig. 4 Flow pattern evolution for the passage gradual opening with a velocity of 100 m/s.

are shown in Fig. 7. The velocity of the passage opening was $V=250$ m/s. It was concluded from the results presented in Fig. 7 that an increase in the initial shock strength leads to stronger reflections and substantial increases in the flow rotation. This, in turn, will lead to increased losses because of mixing of the driver and driven gases. The pattern of multiple reflections of the shock wave from the upper and lower walls of the passage can be seen in Fig. 7a. At time $t=0.073$ ms the shock wave reflected from the upper wall is propagating toward the lower wall. Part of the reflected shock wave front converges with the main shock wave, and part begins to reflect from the lower wall ($t=0.109$ ms). The multiple reflection weakens the reflected shock, but the reflection between the walls of the passage continues and can be followed for $t=0.211$ and 0.245 ms. It is clear that for these conditions even passages with a length-to-width ratio of 6 will have substantial mixing losses because of the rotational flow.

A different situation is found for the passage opening to the inlet port of the driven gas. At this port, the pressure and velocity of the (driver) gas in the passage should be matched with the pressure and velocity of the (driven) gas at the inlet.

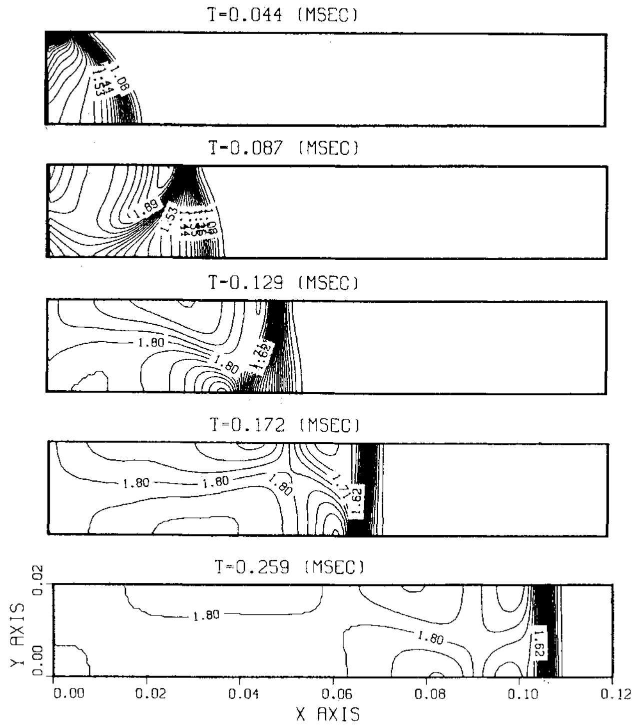


a) Pressure contours.

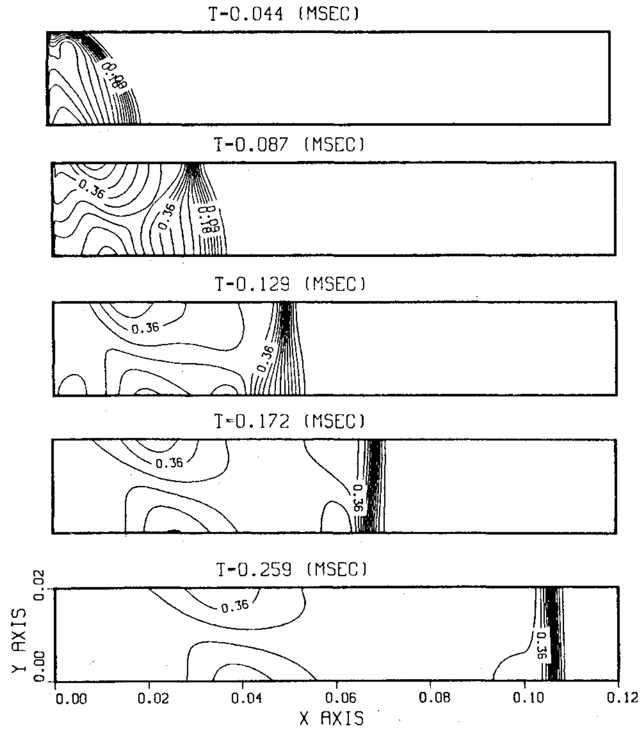


b) Mach number contours.

Fig. 5 Flow pattern evolution for the passage gradual opening with a velocity of 200 m/s.



a) Pressure contours.

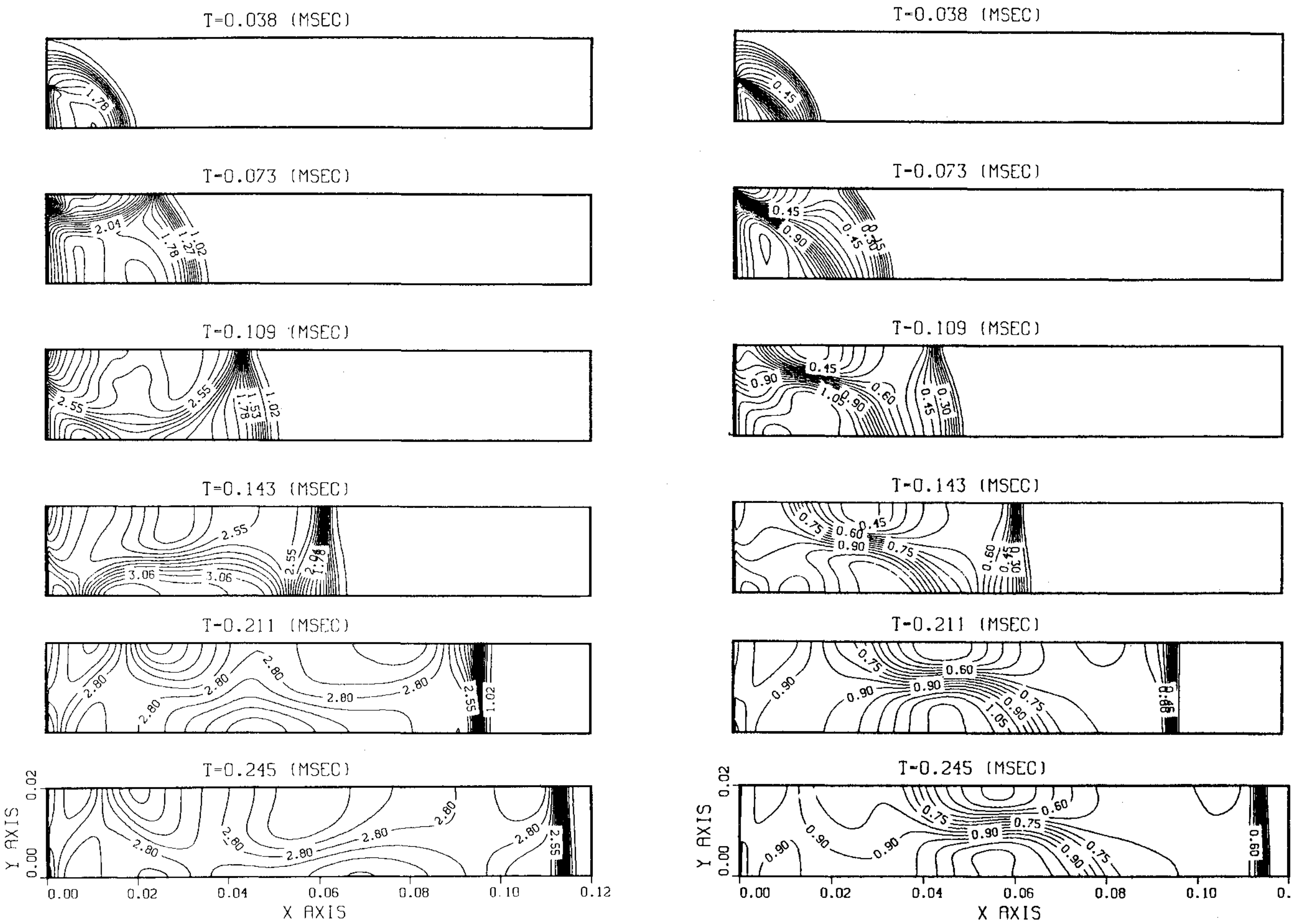


b) Mach number contours.

Fig. 6 Flow pattern evolution for the passage gradual opening with a velocity of 500 m/s.

If the passage opens instantaneously, the flowfield in the passage will have only one discontinuity—the interface between the fresh air and exhaust gas entering and leaving the passage, respectively. To model this condition for the gradual passage opening, it was assumed that in the passage: $P_0 = 1$ atm, $\rho_0 = 0.5$ kg/m^3, $U_d = 150$ m/s, and $V_0 = 0$; in the port: $P_d = 1$ atm, $\rho_d = 1.4$ kg/m^3, $U_d = 150$ m/s, and $V_d = 0$. The velocity of the passage opening was $V = 200$ m/s.

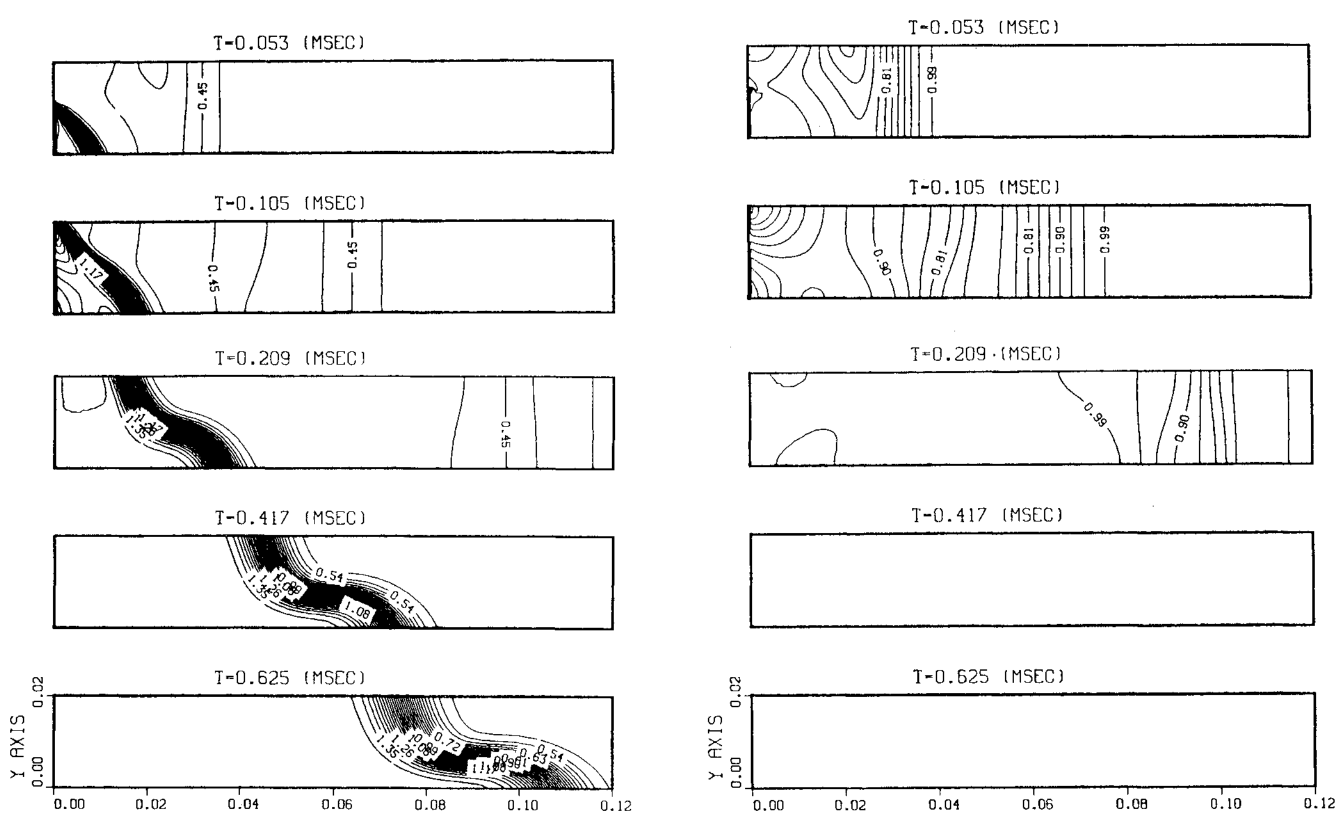
Results for this simulation are presented in Fig. 8. It can be seen that, since at first moment most of the inlet cross section is blocked by the wall, a rarefaction wave reflects from the inlet wall. The passage full opening occurs at $t = 0.1$ ms. From this time on the pressure deviation in the flowfield weakens and at $t = 0.22$ ms the pressure is almost completely uniform and equal to the static pressure in both the undisturbed driven air and exhaust gas. Figure 8b shows that the interface will carry the imprint of the gradual passage opening a long time after the passage becomes fully open. There is no dissipative mechanism included in the mathematical model used in this study to force the interface to become normal to the passage



a) Pressure contours.

b) Mach number contours.

Fig. 7 Flow pattern evolution for the gas with higher total enthalpy at the inlet port.



a) Pressure contours.

b) Density contours.

Fig. 8 Evolution of the interface.

walls. Therefore, the interface will "remember" the dynamics of the gradual passage opening in passages with large length-to-width ratio.

Conclusions

It is shown in the present study, on the basis of numerical modeling, that the dynamics of the passage opening significantly affects the flow pattern in the passages of wave rotor devices. For rectangular axial passages, even when the velocity of the passage opening is 500 m/s, a one-dimensional flow pattern forms only in passages with a length-to-width ratio larger than 3. In the region preceding the formation of the one-dimensional flow pattern, the flow is rotational and, in some instances, contains shock and pressures waves which repetitively reflect from the upper and lower walls of the passage. In practice this would lead to significant mixing between the driver gas (e.g., exhaust gas) and driven gas (e.g., fresh air) and reduce the efficiency of the engine cycle. With a reduction in the velocity of the passage opening, the volume of the mixing region increases as a result of the rotational flow which develops from the slow opening of the passage. With an increase in shock wave strength, the volume of the mixing region increases as a result of the rotational flow which develops form multiple reflections of the shock and pressure waves from the passage walls.

Numerical modeling of the process of gradual passage opening at the inlet port of the driven gas revealed that the interface between the gases will move all the way through the passage with a frozen pattern of distortion or obliqueness to the passage walls. The interface obliqueness increases when the velocity of the passage opening decreases.

In all, it can be concluded that taking into account the gradual passage opening is essential for the wave machine design, not only for proper timing and wave arrangement but also because of the losses which will occur due to mixing and wave reflections. The gap between projected and achieved efficiencies of wave machines[2,6,7] could be partially due to neglect of the effects of the gradual passage opening which are studied herein.

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