A parametric study of shock wave enhancement

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Summary. The flow field developed behind a shock wave propagating inside a constant cross-section conduit is solved numerically. The ambient gas is composed of pairs of air-helium layers having a continually decreasing width. It is shown that a meaningful pressure amplification can be reached behind the transmitted shock wave. By proper choice of the number of air-helium layers and their width reduction ratio, pressure amplification as high as 7.5 can be obtained.

1 Introduction

It is well known that the pressure jump across a given shock wave increases when it propagates in a conduit whose cross-section is continually reduced [1], or in the case of a spherically imploding shock wave [2]. In both cases the flow cross-section is reduced toward zero. A question arises whether or not this is a necessary condition for pressure amplification. In our previous work [3] we have demonstrated that it is possible to create a pressure amplification by using alternating layes of different gases. The gas into which the shock propagates consists of layers of light and heavy gases in which the thickness of each successive heavy layer is less than that of the foregoing. The same is true for the light gas layers.

In the current work a parametric study is conducted with the aim of finding a two layered, light-heavy gas, arrangement that yields maximal shock enhancement. As in our earlier study [3] here too the heavy and the light gases are air and helium, respectively. Effects associated with changes in following parameters were investigated:

- The number of alternating heavy/light gas layers.
- The applied reduction ratio between successive layer's thicknesses.
- The initial shock wave Mach number.

In the current paper it was possible to obtain a pressure amplification that is more than 7.5 times higher than the pressure prevailing behind the incident shock wave. Details regarding the numerical method used in the present solution are given in [3].

2 Results and discussion

In the considered case, an incident shock wave, propagating in helium ($M_s = 2$), collides head-on with alternating layers of air and helium. In the sequence of these layers each successive pair of Air/He layers has half the width of the upstream pair (i.e., layer's reduction ratio, δ, $\delta = 2$). The resulting flow from the interaction of a transmitted shock wave with these layers of Air/He is solved numerically for the following initial conditions: $M_s = 2$, $P_0 = 100$ kPa , $\rho_{air} = 1.25$ kg/m^3 and $\rho_{He} = 0.166$ kg/m^3.

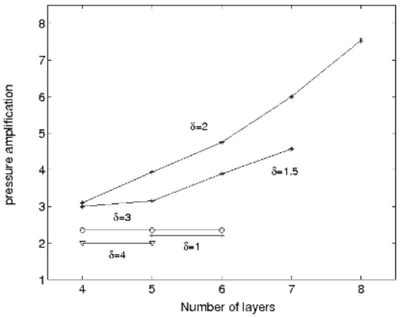

Fig. 1. Pressure amplification versus number of air/helium layers. Initial conditions are: $M_s = 2$, $P_0 = 100$ kPa , $\rho_{air} = 1.25$ kg/m^3 and $\rho_{He} = 0.166$ kg/m^3.

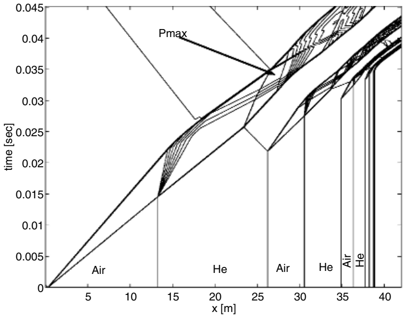

Fig. 2. Density contours for the case having 5 air/helium layers, $\delta = 3$ and other initial conditions as in Fig. 1.

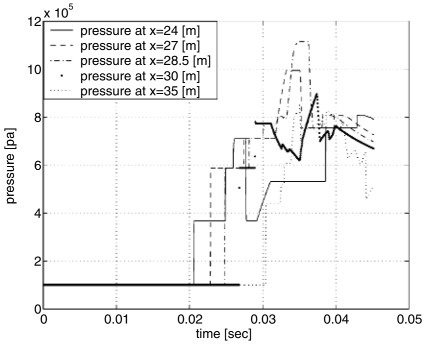

Fig. 3. Pressure histories computed at a few different locations along the conduit for the conditions indicated in Fig. 2.

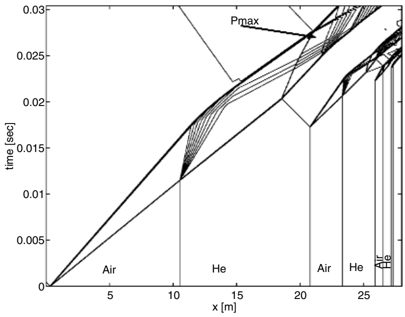

Fig. 4. Density contours for the case having 5 air/helium layers, $\delta = 4$ and other initial conditions as in Fig. 1.

It is reasonable to assume that the attained maximum pressure is influenced by the specific choice of the number of alternating air-helium pair used in the solution and the value chosen for δ. δ is the width ratio between neighboring pair of air-helium layers. In addition, the Mach number of the incident shock wave will most probably influence the value of the attained maximum pressure. In the following these effects are discussed.

As a first step we check the effects associated with changes in the number of alternating heavy-light gas layers on the obtained pressure amplification. By pressure amplification we mean the ratio between the maximum pressure reached behind the transmitted shock wave and the pressure prevailing behind the incident shock wave. In all investigated cases the width of the thinnest (final) layer was kept constant. This was reached by adding appropriately thick layers upstream of the thinnest layer. The initial conditions were kept as mentioned earlier, i.e., $M_s = 2$, $P_0 = 100$kPa ,$\rho_{air} = 1.25$ kg/m^3 and $\rho_{He} = 0.166 kg/m^3$.

Obtained results are shown in Fig. 1 for five different width reduction ratios. For the cases $\delta = 1.5$ and $\delta = 2$ increasing the number of alternating air/helium layers results in

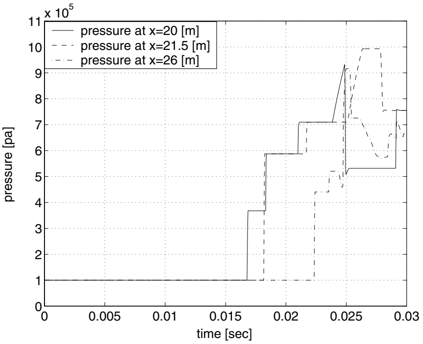

Fig. 5. Pressure histories computed at a few different locations along the conduit for the conditions indicated in Fig. 5.

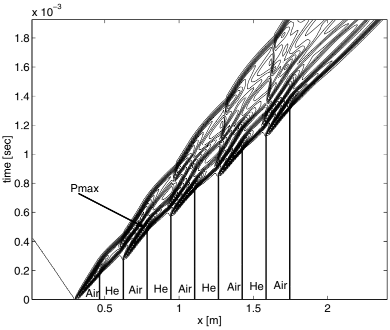

Fig. 6. Density contours for the case having 5 air/helium layers, $\delta = 1$ and other initial conditions as in Fig. 1.

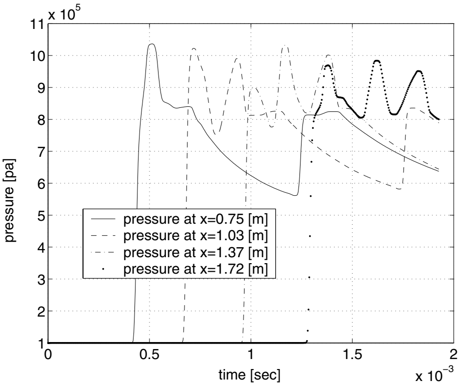

Fig. 7. Pressure histories computed at a few different locations along the conduit for the conditions indicated in Fig. 6.

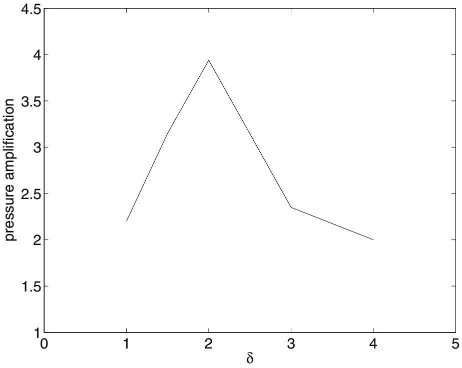

Fig. 8. Pressure amplification ratio. Initial conditions as in Fig. 1 with 5 alternating air-helium layers.

an increase in the obtained pressure amplification. It is also apparent from Fig. 1 that increasing the reduction ratio δ, from 1.5 to 2, for a given number of layers, results in a significant increase in the obtained pressure amplification.

However, when increasing the reduction ratio to 3 or more, increasing the number of layers has practically no effect on the obtained pressure amplifications. The reason for this behavior can be explained by examining Fig. 2 (showing lines of constant density for the case in which $\delta = 3$ and the number of alternating air-helium layers is 5), and Fig. 3. It is evident from Fig. 2 that maximum pressure occurs in the first pair of air-helium layers. It is also evident from Fig. 3 that indeed the highest pressure is found on the curve showing pressure history computed at $x = 28.5$ m, i.e. within the first air-helium layer. Pressure histories computed at either $x < 28.5$ m or $x > 28.5$ m reach a lower maximum pressure. This maximum pressure is about $11 * 10^5$Pa, which results in a pressure amplification of 2.31 only.

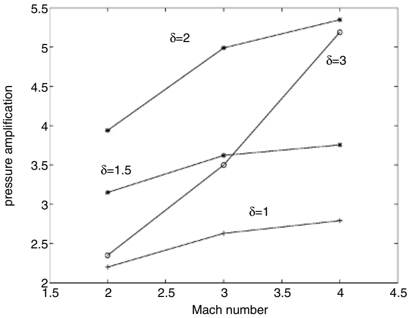

Fig. 9. Pressure amplification versus the incident shock wave Mach number.

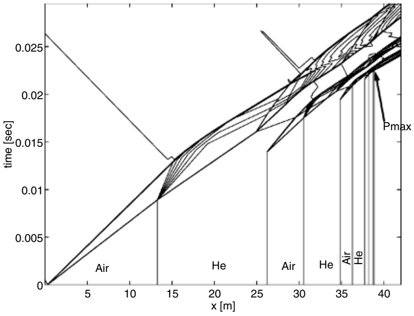

Fig. 10. Density contours for the case having 5 air/helium layers, δ=3 Initial conditions are: $M_s = 3$, $P_0 = 100$ kPa , $\rho_{air} = 1.25$ kg/m^3 and $\rho_{He} = 0.166$ kg/m^3.

A significantly higher value is reached when δ=2 and the number of alternating air-helium layers was 6. At these conditions: $P_{max} = 2.2 * 10^6$ Pa. In addition, for δ=2 and 5 layers a pressure amplification of about 4 was obtained as shown in Fig. 1. However in both cases when δ=2 the maximum pressure was in the thinnest air layer. Similar behavior is observed when changing the number of alternating air/helium layers to 4 and δ to 4. It is evident from Fig. 4, showing lines of constant density, that here again maximum pressure is reached within the first pair of air-helium layers. It is suggested in Fig. 5 that this maximum pressure is only 10^6 Pa; significantly smaller than that observed for δ=2 where the maximum pressure is reached further downstream (at the thinnest air layer). As a reference, results obtained for the case in which the number of alternating air-helium layers is 5 and δ=1 (i.e., a sequence of alternating air-helium layers all having the same width), are shown in Figs. 6 and 7. It is evident from these figures that maximum pressure is reached in the first pair of air/helium layers and this maximum is barely over 10^6Pa. In summary it is apparent that maximum pressure amplification is reached when δ=2 as shown in Fig. 1.

The next parameter to be checked is the reduction ratio, δ; effects associated with changes in δ on the obtained pressure amplification are shown in Fig. 8. In this case the number of air/helium layers was kept constant at 5 and all other initial condition are as in the previous case. As already shown (in Fig. 1), increasing δ within the range $1 < \delta < 3$ results in meaningful pressure amplifications. However, further increase in δ results in significant decrease in the obtained pressure amplification. It was shown that for $\delta > 3$ the maximum pressure is reached in the first pair of air/helium layer thereby excluding further pressure amplification.

The last case to be studied is the effect that changes in the incident shock wave Mach number have on the obtained pressure amplification. In this case the number of air-helium layers was set at 5 and the following values of δ were investigated; $\delta = 1$, 1.5, 2 and 3. Other initial conditions were kept as in the previous cases. Summary of the obtained results are shown in Fig. 9. The following is apparent from Fig. 9.

- As could be expected for all δ's, increasing the incident shock wave Mach number results in an increase in the obtained pressure amplification.

- For $1 < \delta \leq 2$ a similar (moderate) increase in pressure amplification is observed when increasing the incident shock wave Mach number. However, for $\delta = 3$ a significantly larger increase in pressure amplification is evident for increasing values of M_s. The reason for this behavior is the fact that when $1 < \delta \leq 2$ the maximum pressure is achieved in the thinnest air layer while in the case when $\delta = 3$, for $M_s = 2$ the maximum pressure is found in the first pair of air/helium layer (the thickest layers, see Figs. 2 and 3); it moves to thinner layers when M_s is raised above 2. It is apparent from Figs. 10 and 11 that with increase in the incident shock wave Mach number (to $M_s = 3$) the maximum pressure is found in the thinnest layer.
  The fact that in the considered case the highest pressure is found in the thinnest layer is similar to what was observed in [3], where results obtained for δ=2, are shown. It is also evident from Fig. 11 that indeed the highest pressure is found on the curve showing pressure history computed at $x = 38.86$ m, i.e. within the thinnest air layer. Pressure histories computed at $x < 38.86$ m reach lower maximum pressure. This maximum pressure is about $38 * 10^5$Pa, which yields a pressure amplification of 3.5.

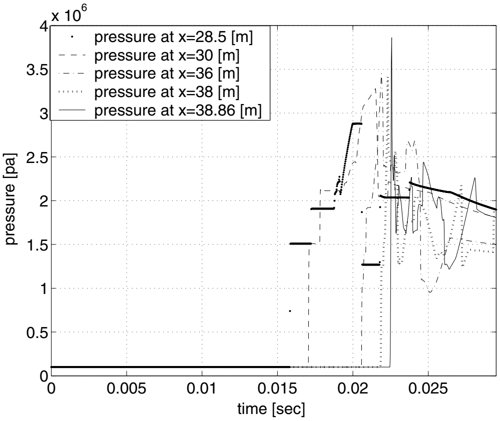

Fig. 11. Pressure histories computed at a few different locations along the conduit for the conditions indicated in Fig. 10.

3 Conclusions

It is shown that significant shock wave enhancement is achievable in a one-dimensional flow (constant flow cross-section) by employing alternate layers of heavy and light gases. Several parameters affecting the alternating air-helium layers were studied to find out how to obtain maximal pressure amplification. It was shown that in the case when $M_s = 2$, δ= 2 and the transmitted shock wave passes through 8 alternating air/helium layers a pressure amplification of about 7.5 is possible. Higher pressure amplifications can be reached by increasing the number of alternating air/helium layers.

References

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