Suppression of Shock-Induced Separation in Dense Gases
비열이 큰 유체에서 발생하는 충격파 유발 박리 현상의 억제에 관한 연구

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Key Word : Shock(충격파), Separation(박리현상), Discontinuity(물성의 불연속), Disintegration(분해), Inviscid(비점성의), Viscous(점성의)

ABSTRACT:We consider the reflection of oblique compression waves from a two-dimensional, steady, flat-plate, laminar boundary layer. The full Navier-Stokes equations are solved numerically through use of a dense gas version of the Beam-Warming implicit scheme. In the classical perfect gas theory the compression waves are necessarily shocks. As is well-known, the adverse pressure gradient carried by these shocks can lead to boundary layer separation.

In the present investigation we consider the behavior of Bethe-Zel′dovich-Thompson (BZT) fluids in the context of this classical benchmark problem. Bethe-Zel′dovich-Thompson (BZT) fluids are ordinary gases which have specific heats large enough to cause the fundamental derivative of gasdynamics (1) to be negative over a finite range of temperatures and pressure in the single-phase vapor regime. Here ρ, p, α, and s are the fluid density, presure, sound speed, and entropy, respectively. The quantity $V \equiv \rho^{-1}$. When $\Gamma < 0$ everywhere in a particular flow, compression discontinuities are known to violate the entropy inequality. If such an inadmissible discontinuity is introduced into a flow, e.g., by a wedge or a sharp leading or trailing edge of a turbine blade, it naturally disintegates into a centered fan. Thus, the adverse pressure gradient carried by the compression wave is significantly reduced by the natural inviscid dynamics of $\Gamma < 0$ fluids. The purpose of the present study is to determine whether this reduction in the adverse pressure gradient can suppress boundary layer separation. We make direct comparisons between the behavior of BZT fluids and more conventional fluids such as steam. The primary result of interest is that this suppression of separation can indeed be achieved. The physical mechanism for the suppression is discussed as are strategies for realizing the suppression in practical configurations.

1. Introduction

An important loss mechanism in both turbomachinery and aerodynamic flows is cauesd by the shock-induced separation of boundary layers. The physical mechanism behind shock-induced separation is caused by the strong adverse pressure gradients carried by compression shocks which originate either at neighboring blades in the case of turbomachinery, other portions of the fuselage or aerodynamic surfaces in the case of supersonic aircraft or which form on the wing or fuselage itself in the case of transonic flow. For a given pressure rise, shock waves are more likely to separate the boundary layer because the pressure gradient of the incoming signal is infinite, at least in the context of the inviscid theory.

In most flows of practical interest regions of flow compression are inevitable and in supersonic and transonic flows of perfect gases these compressions inevitably steepen to form compression shocks which in turn carry the strong adverse pressure gradients leading to flow separation.

In recent years it has been shown that such steepening is not inevitable if the class of fluids considered is extended to include high pressure gases. By high pressure we mean pressures which are so large that ideal gas law no longer provides accurate description of the gas behavior. At such pressure levels more complicated equations of state, such as the van der Waals equation, are required. We will also refer to such high pressure conditions as dense gas conditions. It is the principal goal of the present study to demonstrate that shock-induced separation can in fact be suppressed through use of a class of commercially available fluids operating at moderate pressure levels.

The fluids considered here are of the Bethe-Zel′dovich-Thompson (BZT) type. These are ordinary gases which have specific heats which are so large that the fundamental derivative of gasdynamics

$$\Gamma \equiv \frac{a}{\rho} + \left.\frac{\partial a}{\partial \rho}\right|_s = \frac{V^4}{2a} \left.\frac{\partial^2 p}{\partial V^2}\right|_s \tag{1}$$

becomes negative over a finite range of pressures and temperatures in the single-phase vapor regime. Here ρ, p, s and a are the fluid density, pressure, entropy and thermodynamic sound speed. The quantity $V \equiv \rho^{-1}$ is referred to as the specific volume. We also refer to the thermodynamic quantity (1) as the intrinsic gasdynamic nonlinearity parameter. For descriptions of the nonclassical dynamics of BZT fluids we refer the reader to the introductions and summaries of Bethe (1942), Zel′dovich (1946), Thompson (1971), Thompson and Lambrakis (1973), Menikoff and Plohr (1989), and Cramer (1991). Here we simply point out that the well-known compression discontinuities of the perfect gas theory violate the entropy inequality if $\Gamma < 0$ at all points in the neighborhood of the proposed discontinuity. If such an inadmissible discontinuity is introduced into a $\Gamma > 0$ flow, say by a wedge inserted in a supersonic $\Gamma < 0$ flow, it disintegrates into a centered compression reminiscent of the well-known Prandtl-Meyer fans of the perfect gas theory. This disintegration process was first discussed in the context of steady supersonic flows by Thompson (1971).

The potential advantages of BZT fluids with respect to shock-induced separation should now be obvious. Although the disintegration of the compression discontinuity does not change the polarity of the signal, i.e., it remains a compression, it does in fact significantly reduce the gradient. That is, the incoming compressive signal arriving at the boundary layer is of nonzero length rather than the zero length associated with shock waves. Intuition based on the perfect gas or even incompressible flow theory strongly suggests that such a reduction in the adverse pressure gradient experienced by the boundary layer should result a reduction or even elimination of shock-induced separation. In present investigation, we demonstrate that such a suppression of shock-induced separation can indeed occur.

If such a reduction or suppression of separation can be realized in BZT fluids it is natural to ask whether these nonclassical dynamics can be exploited in technology. One of the most promising application of BZT fluids is as working fluids in organic Rankine cycles. These power cycles are ordinary Rankine cycles which employ retrograde fluids as working fluids for geothermal and solar applications and waste heat recovery. The advantage of retrograde fluids is that they dry upon adiabatic expansion rather than condense. Organic Rankine cycles therefore eliminate the need for superheating and therefore require less capital cost, system weight and complication. A general discussion of the advantages of organic Rankine cycles has been given by Curran (1981), Yan and Svedberg (1991) and Angelino and Invernizzi (1993). In order to save space we will restrict our comments to pointing out that BZT fluids tend to be a subclass of retrograde fluids and turn out to be excellent candidates for use as working fluids in such power systems. Not only do BZT fluids have all the advantages of other retrograde fluids but they also have the potential to reduce or eliminate shock-induced separation in the turbine stage of the cycle.

2. Formulation

To illustrate the suppression of separation we consider the classical benchmark problem of the reflection of an oblique shock from a laminar flat-plate boundary layer. The flow conditions are chosen so that the reflection is regular. As a result the flow is supersonic everywhere in the inviscid part of the flow. The governing equations are taken to be the two-dimensional steady flow Navier-Stokes equations. These are solved numerically by the well-known Beam-Warming (1978) implicit scheme which has been generalized to account for dense gas effects. A full description of the scheme used and the battery of consistency checks performed have been given by Park (1994).

The equation of state is the state of the art model developed by Martin and Hou (1995). The dense gas viscosity and thermal conductivity models chosen were those developed by Chung et al (1988). Each of these models, the treatment of bulk viscosity and the physical data for the fluids employed here are described in detail by Park (1994).

Finally, we note that the flows considered here are all single-phase. The saturated vapor line correlation of Riedel (1956) was used to ensure that all computed points in the flowfield correspond to the single-phase gas regime.

3. Results

In the present study we have compared the behaviors of two fluids. The first is ordinary steam which was chosen because of its widespread use in Rankine power cycles and the fact that is not a BZT fluid, i.e., $\Gamma > 0$ for all pressures and temperatures. The second fluid is the commercially available BZT fluid perfluoro-trihexylamine ($C_{18}F_{39}N$) and will be referred to by its trade name FC-71. As pointed out in Section 2, a full discussion of the physical property data for each fluid is given by Park (1994) and the references therein.

We have attempted to make direct comparisons between the fluids. For each fluid the freestream pressure, temperature, Mach number, and impingement Reynolds number was fixed at 8.55 atm, 646.15 K, 2.0, and 2.96×10^5, respectively. We note that the freestream pressure of 8.55 atm is only about 4% of the pressure at steam's thermodynamic critical point. As a result the flow of steam can be regarded as that of a perfect gas. For both fluids the incident shock carries a flow deflection angle of 3° . Thus, the incident shock strength can be regarded as essentially the same for each fluid.

The resultant variation of the plate skin friction coefficient c_f is depicted in Figure 1. There x is the coordinate measured parallel to the undisturbed flow direction. The leading edge of the plate was taken to be at $x=0$ and the shock impingment point is given by $x=L_s$. The circles denote the variation for steam. The separation is seen to be well-developed with two local minima in c_f . The ++++ symbols denote the variation of c_f for the BZT fluid FC-71. Here $c_f > 0$ for all x and no separation is therefore observed. A check on flow details reveals that the values of $\rho\Gamma/\alpha$ immediately upstream of the incoming compression are -0.04 and -0.16. The theory developed in the references by Bethe, Zel′dovich, Thompson, etc. can be used to show that the initial compression discontinuity in FC-71 is inadmissible and therefore has disintegrated into a centered fan. As a result the adverse pressure gradient is too weak to separate the boundary layer. An examination of a number of shock-boundary layer interations and pure boundary layer flows in dense gases reveals that the reaction of the viscuos boundary layer is essentially classical. As discussed by Park (1994), the primary physical mechanism for this suppression is the disintegration of the shock and the resultant weakening of the adverse pressure gradient of the incoming inviscid signal.

We should also note that the relative widths of the interaction zones do not necessarily correspond to those of the physical flow. This is due to the fact that the streamwise coordinate x has been scaled with L_s, the dimensional distance from the the leading edge required to attain the impingment Reynolds number of 2.96×10^5. Because the density, shear viscosity and sound speed differ for steam and FC-71, the value of L_s will differ as well. The actual width of the FC-71 interaction zone can be considerably wider than that of steam.

Finally, we have also included the computed variation of c_f for FC-71 at the same freestream temperature and Mach number, the same impingement Reynolds number and the same incoming shock strength as in the previous examples. This variation is given by xxxxx symbols in Figure 1. The only new feature in this case is that the freestream pressure was taken to be 1 atm instead of 8.55 atm. As a result, the FC-71 behaves as a nearly perfect gas and $\Gamma>0$ everywhere in this flow. The initial compression discontinuity remains intact as a shock and, as seen in Figure 1, separates the flow. In fact, aside from the x-stretching mentioned above, the skin friction variation is very similar to that of steam. The point of this additional calculation is that it supports the idea that the suppression of separation is primarily due to the differences in the incoming inviscid signal and not due to differences in some other possible viscous detail of the fluid behavior. Furthermore, this demonstrates how one can eliminate separation simply by increasing the pressure to bring the state from the ideal gas conditions to one corresponding to a negative Γ flow.

Fig. 1. Computed skin friction coefficients. The open circles denote steam at a freestream pressure of 8.55 atm, the ＋＋＋＋ symbols denote FC-71 at a freestream pressure of 8.55 atm and the xxxx symbols denote FC-71 at a freestream pressure of 1 atm.

4. Summary

We have employed a dense gas version of the Beam-Warming implicit scheme to compare the viscous-inviscid interactions of steam to that for a BZT fluid at the same freestream conditions, the same shock impingement Reynolds number and the same strength incoming signal. It is found that the natural dynamics of BZT fluids in their Γ〈0 regime leads to a disintegration of the initial compression discontinuity. As a result of this reduction in the adverse pressure gradient shock-induced separation was suppressed in the BZT fluid. The author feels that the discovery that the suppression is primarily due to the inviscid dynamics can lead to considerable simplification in attempts to exploit this behavior. One can employ perfect gas intuition when considering the viscous parts of the flow and restrict any optimizations to the inviscid flow regions.

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