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Detonation interaction with wedges and bends

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Abstract. The paper reports the results of a series of studies on the interaction of gaseous detonations with obliquely inclined surfaces. Interactions of increasing complexity are described in turn: at a planar inclined wall, two-dimensional propagation in a curved channel and finally three-dimensional interaction with a bend in a cylindrical pipe. The role of detonation structure is discussed as well as the magnitude and duration of potentially damaging overpressures.

Key words: Detonation, Diffraction, Reflection, Wedges, Bends

1 Introduction

Many studies exist on shock reflection from wedges and more recently an increasing number of investigations have also been undertaken on detonation reflection. Yet, for detonations at least, some questions still remain unanswered. One fundamental question is how differences in detonation structure will influence the reflection process. There is also a practical interest, arising from the need to quantify the consequences of detonations in pipes and especially the effects of bends. The main cause for concern in this instance is the level of pressure enhancement generated by the partial reflection of the detonation front from the oblique surfaces in pipe bends.

To help understand more fully the processes that are likely to arise in complex three-dimensional geometry it is useful to first review detonation reflection in a planar geometry and then investigate a two-dimensional curved geometry. In the present paper we therefore briefly review existing knowledge on detonation interactions with planar wedges and present further new observations of such interactions, including a study of the influence of detonation structure. Some brief observations of the propagation of detonations in two-dimensional curved channels are then reported. Finally, the results of an initial observation of detonation propagation in a pipeline bend are given.

2 Previous studies of detonation interaction with wedges

Extensive work, both experimental and theoretical, has been carried out to investigate the reflection of shocks in non-reactive gases by planar wedges. Certainly, for strong shocks, the phenomena is understood fairly well, see for example Ben-Dor (1991) and Glass and Sislian (1994). Less work has been done on the more complex reflection of detonations by planar wedges. Unlike a shock, a planar detonation front is actually comprised of many smaller reactive shock structures in a Mach configuration. These waves interact with each other and give rise to regions of intense exothermic chemical reaction. It is these transverse wave interactions that support the main detonation wave, see Nettleton (1987). Changes in the chemical composition and initial pressure of the detonable gas will lead to changes in the dominant time-scales for these energy release processes and hence they also determine the scale of the intricate flow fields within the detonation front. The result is the cellular structure characteristic of detonation. It is a variation in this structure that could potentially influence the reflection process.

As with shocks, below a critical inclination, a Mach stem and a reflected shock are super-imposed on the main incident detonation front, resulting in two flow regions as the detonation front propagates over a wedge. Different cell sizes are observed in the two regions behind the incident front and the Mach stem, separated by the triple point. At higher wedge angles regular reflection occurs. Of the previous studies reported, Gvozdeva (1964), Gvozdeva and Predvoditeleva (1969) studied the reflection of CH_4+2O_2 detonations. Studies of both $2H_2+O_2$ and $C_2H_2+2.5O_2$ were undertaken by Gavrilenko and Prokhorov (1983) whilst experimental work on $2H_2+O_2$ was also performed by Meltzer (1990) and Meltzer et al. (1991). Edwards et al. (1984) had earlier studied $2H_2+O_2+Ar$, $C_2H_2+2.5O_2$ and $C_2H_2+2.5O_2+8.2Ar$.

Further, experimental studies with $2H_2+O_2$ were reported by Ohyagi et al. (1997) whilst Ohyagi et al. (2000) undertook numerical simulations of previous experimental results. Analytical studies of detonation reflection have also been reported by Li et al. (1997). Zhang et al. (1997) reported results with C_2H_2+air at a larger scale.

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In general the works cited above have considered detonations with relatively regular structure. Moen et al. (1986) however have shown that finer sub-structure (especially obvious at the start of the cell) can alter the conditions required to initiate a detonation or to increase its ability to resist external perturbations. It is possible therefore that changes in the characteristic structure of a detonation front could influence the Mach reflection process.

3 Laboratory studies

During the present studies experiments were undertaken at both laboratory and field scale. Laboratory experiments were used to study detonation propagation over a planar wedge and through a two-dimensional curved channel. A range of gas mixtures were tested with the aim of investigating the influence of detonation cell structure on the reflection process. These included stoichiometric hydrogen-oxygen undiluted or diluted with 50% argon or nitrogen and stoichiometric ethane-oxygen with 50% argon dilution. The field scale tests were used to measure the peak pressure generated as an ethylene-air detonation propagated through a bend in a 300 mm diameter pipe.

The laboratory experiments were performed in two standard rectangular cross-section detonation tubes, each just over 4 m in length. A 76 mm × 38 mm cross-section tube was used for the wedge studies while a 76 mm × 6 mm tube was used for the channels studies. Stoichiometric ethylene-oxygen at an initial pressure of 40 kPa was used as the driver gas in all cases. This driver mixture was ignited by means of a spark which rapidly transits to detonation bursting the Melinex diaphragm separating the test and driver gases, thereby rapidly initiating a detonation in the less reactive test gas. For the planar wedge studies either a smoked foil section was placed at the end of the main detonation tube, or a special section fitted with windows suitable for schlieren photography was used. The planar wedges were formed by placing various Duralumin pieces in the smoked foil or window section at the end of the tube. Pressure records were also obtained from three pressure gauges placed flush with the inside wall of the tube. Two gauges were placed upstream of the wedge, to monitor the incident detonation wave, and a third was placed immediately above the plane of the wedge. The peak pressure due to an overdriven detonation in the Mach stem could thus be measured and compared to that of a C-J detonation.

To allow detonation propagation through the two dimensional channel to be studied, 6 mm wide sheets of Tufnol were machined to give a channel 15 mm in height and 6 mm deep. The short radius bend was formed from walls of radii 14.5 and 29.5 mm whilst for the longer radius bend wall the radii were 40.5 and 55.5 mm, respectively. The machined pieces were fixed firmly to the walls of the smoked foil section in the 76 mm × 6 mm tube.

4 Detonation-wedge interactions

4.1 Smoked foils

It is well known from previous shock and detonation studies that either regular or Mach reflection occurs dependent on whether the wedge angle θ is greater or less than some critical angle θ_c. The range of reflection behavior observed is illustrated in the smoked foil records reproduced in Fig. 1, obtained with the mixture $2H_2+O_2+Ar$ at an initial pressure of 20 kPa. The Mach stem is not easily identified at first but, as the wedge angle θ is increased, the inclination of the triple point locus χ becomes more evident until, at around 46°, it is no longer possible to identify any Mach stem. Similar results were obtained with other initial pressure and mixtures, see Williams (1996). The influence of changing the mixture composition and diluent can be seen in Figs. 2 and 3.

Figure 2 shows smoked foils images obtained with undiluted $2H_2+O_2$ and the more regular $2H_2+O_2+3Ar$. Both, again, for an initial pressure of 20 kPa, at a fixed wedge angle of 20°. Also shown are the smoked foil records obtained along the wedge surface.

Figure 3 shows foils for two mixtures with more ‘irregular’ cell structure. These are hydrogen-oxygen diluted with nitrogen, $2H_2+O_2+3N_2$, and ethane-oxygen which is irregular even when diluted with argon, $C_2H_6+3.5O_2+4.5Ar$. The wedge angle in Figs. 3a,b is again 20° and the initial pressures are 20 and 10 kPa, respectively. When the argon was replaced by nitrogen dilution in the ethane mixture, at the same initial pressure, it was virtually impossible to determine any specific trajectory for the reflection Mach stem. A general indication of the locus was given by differences in the local orientation of the detonation structure, which is usually aligned normal to the local direction of propagation of the detonation front. For the ethane mixture the fine structure close to the wedge is particularly affected by large scale transverse waves propagating downwards towards the wedge surface. Figure 3 also illustrates how the cellular structure changes for hydrogen-oxygen when the diluent is changed from argon (see Fig. 2) to nitrogen.

Nearly all of the smoked foils noted above show a region of larger cells at the base of the wedge before the establishment of a subsequent steady state with smaller cell sizes. The distance along the wedge at which this transition occurs increases with wedge angle. This does not occur however with the ethane mixture where the cells at the base of the wedge are initially very ‘fine’ and increase in size along the wedge. The Mach triple point trajectory angle χ appears to be clearly defined by a locus of finer structure in the Mach stem region. The validity of this observation will be discussed in greater detail later.

4.2 Spark schlieren photographs

Spark schlieren photographs obtained with $2H_2+O_2+Ar$ are shown in Fig. 4 for increasing wedge angles. The transverse wave structure in the incident wave is just visible