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PRESSURE DISTRIBUTION INSIDE PIPES DUE TO DDT

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ABSTRACT

The ignition of a flammable gas mixture contained within a piping system can lead to damage or failure of the piping or system components. Flame propagation and acceleration within piping systems have been extensively studied. It has been well documented that, given sufficient flame propagation distance and/or the presence of turbulence generating features, flame acceleration within a pipe can lead to a deflagration-to-detonation transition (DDT). The high overpressures associated with a DDT can increase the potential for deformation or failure of the piping system relative to the loads associated with either a fast deflagration or steady-state detonation. This paper presents the results of numerical evaluations to predict the pressure distributions within a pipe run due to a DDT. The blast overpressure associated with a DDT was found to depend on a number of parameters, including: the rate of flame acceleration prior to the DDT, the length of piping occupied by the flammable mixture, the initial gas pressure and the flammable mixture concentration distribution along the pipe. This paper also provides a comparison of the blast loads associated with a steady-state detonation relative to those due to a DDT.

INTRODUCTION

The ignition of a flammable gas mixture contained in a piping system can lead to damage or failure of the piping or system components. Flame propagation and acceleration within piping systems have been extensively studied. It has been well documented [1-5] that, given sufficient flame propagation distance and/or the presence of turbulence generating features, flame acceleration within a pipe can lead to a deflagration-to-detonation transition. The high overpressures associated with a DDT can increase the potential for deformation or failure of the piping system relative to the loads associated with either a fast deflagration or a steady-state detonation.

This paper presents the results of numerical evaluations of the pressure distributions within a pipe run due to a DDT. The BWTI™ (Blast Wave-Target Interaction) computational fluid dynamics (CFD) program was used to examine a number of parameters associated with a DDT, including: the rate of flame acceleration prior to the DDT, the length of piping occupied by the flammable mixture, the initial gas pressure and the flammable mixture concentration distribution along the pipe.

FLOW FIELD UNDER CONSIDERATION

Figure 1 shows the flow field that was modeled for this work. The flow field consists of a straight pipe of length L_{Pipe} (= 400 ft) with two closed ends. One half of the pipe (L_{Cloud} = 200 ft) contains a flammable gas mixture. The mixture is ignited at the left end of the closed pipe. It is assumed that flame acceleration due to the confinement and roughness of the pipe wall (or obstacles within the pipe) will result in a DDT at a distance of L_{DDT}, which was taken to be 110 ft. Figure 2 depicts the prescribed flame speed (Mach No.) versus distance from the ignition location. The steady detonation Mach No. was assumed to be 5.2. Four acceleration rates were examined in this analysis. In each case, the equation shown below for the flame Mach No. as a function of the distance was used:

$$M_S = a + bX^{N1} + cX^{N2}$$

Where

M_S = *Flame speed Mach number*
X = *Dimensionless distance* x/L_{DDT}
x = *Distance from ignition*
L_{DDT} = *Distance from ignition to DDT (assumed 110 ft)*

The coefficients *a, b, c, N1* and *N2* for the four cases examined in this analysis are provided in Table 1. These coefficients were selected to represent differing levels of flame acceleration between the point of ignition and DDT. The acceleration rate near the location of the DDT was classified as either "fast" (Case 11, 12 and 13) or "slow" (Case 21), depending on the exponent N2. Of course, the use of the terms fast and slow within this discussion is intended to be on a relative basis rather than an absolute basis.

The corresponding flame Mach No. versus time is given in Figure 3.

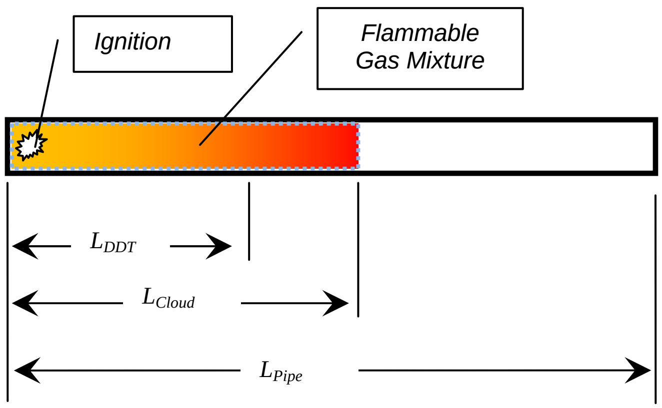

FIGURE 1. SCHEMATIC OF FLOW FIELD MODELING

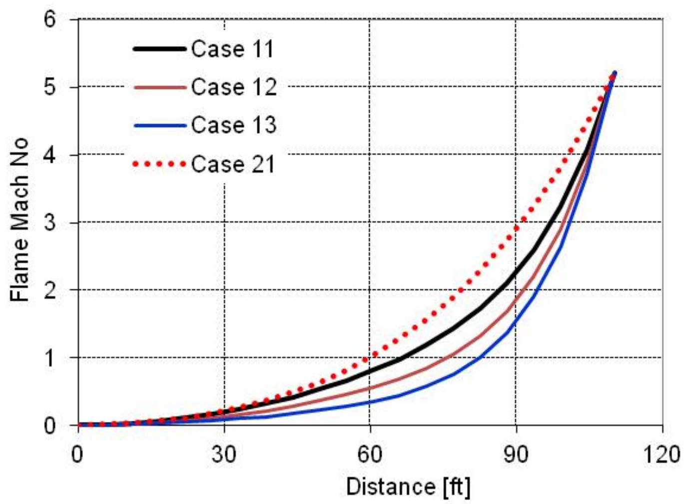

FIGURE 2. FLAME MACH NUMBER VS DISTANCE

TABLE 1.
COEFFICIENTS OF ACCELERATION CORRELATION

	a	b	c	N1	N2	Acceleration Rate Near Point of DDT
Case 11	0.01	2.6	2.6	2	8	Fast
Case 12	0.01	1.73	3.47	2	8	
Case 13	0.01	1.04	4.16	2	8	
Case 21	0.01	2.6	2.6	2	4	Slow

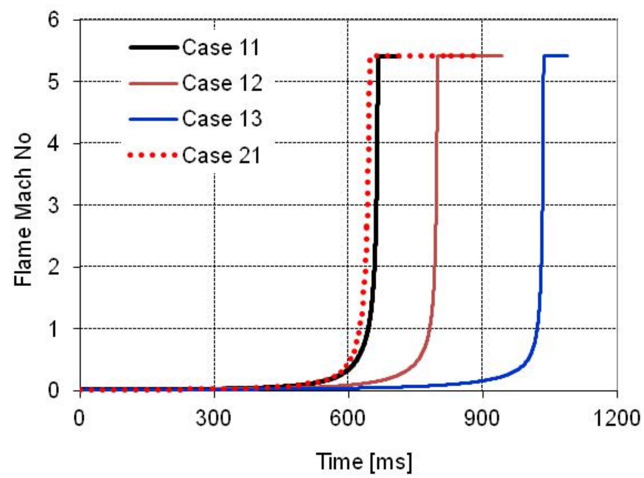

FIGURE 3. FLAME MACH NUMBER VS TIME

NUMERICAL MODEL

The BWTI™ (Blast Wave Target Interaction) simulation package was used to evaluate blast loads for the purposes of this evaluation. BWTI™ is an integrated CFD code and visualization system developed to provide the capability to simulate the generation and propagation of blast and shock waves along with the interaction of such waves with structures (e.g., buildings, blast walls, etc.). BWTI™ has the capability to model the blast waves resulting from high explosive (HE) detonations, pressure vessel bursts (PVB) and vapor cloud explosions (VCEs) [6,7]. The two-dimensional (2D) version of BWTI™ was employed in this evaluation.

The BWTI™ code does not simulate the turbulent combustion directly. Instead, the concept of an energy wave with a prescribed flame speed was adopted [8]. The energy release rate of the wave is controlled by the wave thickness which depends on the flame speed (i.e., the energy wave thickness is a function of the flame speed). An example of the pressure histories for a steady-state detonation in the pipe with a Mach No. of 5.2 is given in Figure 4. The peak overpressure reaches approximately 450 psig (31.8 barg).

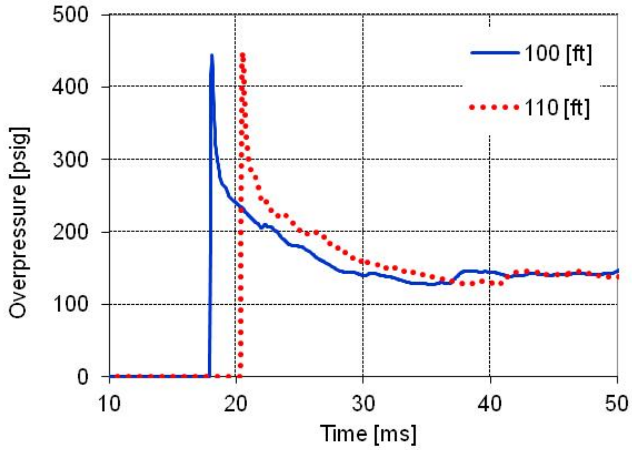

FIGURE 4. STEADY DETONATION WAVE IN PIPE AT SELECTED LOCATIONS

RESULTS AND DISCUSSION

Overpressure vs Distance

Figure 5 shows pressure histories at selected locations for Case 11. As noted earlier, a pipe length of 400 ft, a flammable gas column length of 200 ft, and a distance to DDT of 110 ft were assumed for the purposes of this analysis. An overdriven detonation yields a peak pressure of around 1300 psig just past the location where the DDT occurs (i.e., 110 feet), compared to 450 psig for the steady-state detonation wave. The region of very high pressure is localized to near the DDT location. For example, pressures above roughly 1200 psig are restricted to a narrow zone about 5 ft long (between 110 ft and 115 ft).

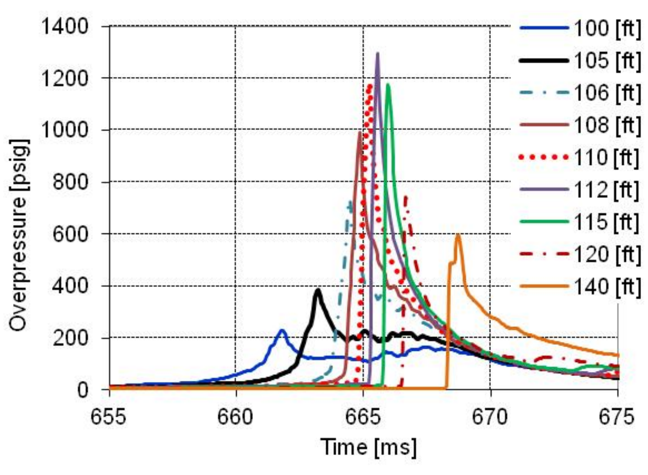

FIGURE 5. PRESSURE HISTORIES AT SELECTED LOCATIONS (CASE 11, 400 FT PIPE)

Influence of Flame Acceleration Rate

The peak overpressure distribution along the pipe is summarized in Figure 6 for all acceleration rate cases considered in this analysis. The overpressure for the steady-state detonation is included in the figure as a reference. Cases 11 through 13 (i.e., fast acceleration) yield a similar behavior in terms of the peak pressure, while Case 21 (i.e., slow acceleration) generates significantly lower peak overpressures.

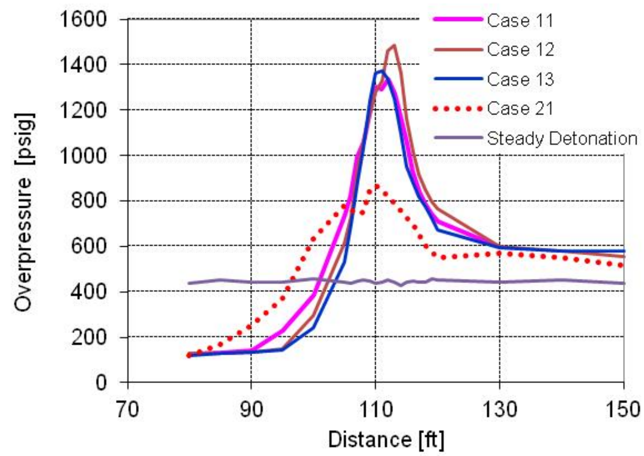

FIGURE 6. PEAK OVERPRESSURE VS DISTANCE (400 FT PIPE)

Adjustment Factors

To quantify the DDT overshoot pressure (i.e., the peak overpressure with a DDT relative to that for a steady-state detonation wave), the overpressure adjustment factor (AF) was introduced. The adjustment factor is expressed as the ratio of the peak overpressure for a DDT to the steady-state detonation peak pressure.

Figure 7 shows overpressure adjustment factors for all acceleration rate cases considered in this analysis. The overpressure AFs for the fast and slow acceleration cases are approximately 3.0 and 2.0, respectively.

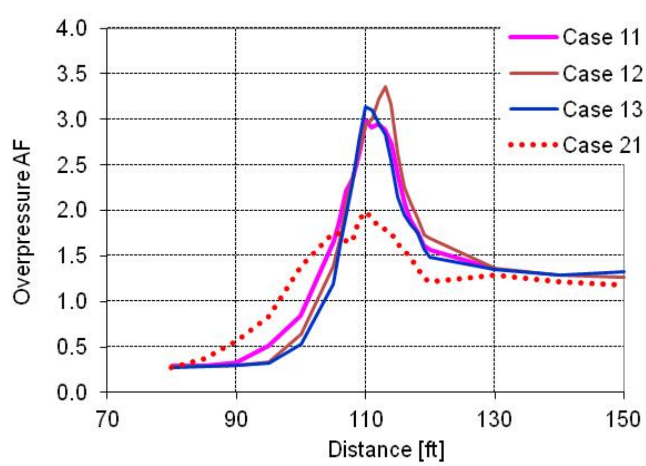

FIGURE 7. DEPENDANCE OF PRESSURE AF ON ACCELERATION RATE (400 FT PIPE)

Influence of Pipe Length

The results for a 400 ft long closed pipe were presented in the previous section. Figure 8 shows the influence of the pipe length on the overpressure adjustment factors. The flame acceleration rate of Case 11 was employed for this comparison. The overpressure AF increases from 3.0 to more than 3.5 as the pipe length is decreased by a factor of 2 (i.e., 400 ft to 200 ft).

The reason that the shorter pipe lengths produce higher pressure AFs can be explained as follows. As discussed in the previous section (Figure 2 and Figure 3), the flame Mach number does not exceed 1 prior to 640 ms (Figure 2), which corresponds to a flame travel distance of 66 ft (Figure 3). The burning gas behind the accelerating flame expands and increases the gas pressure ahead of the flame. With decreasing L_{Pipe}, the gas pressure ahead of the accelerating flame increases more for shorter pipes. The DDT overpressure (or the overpressure AF) is increased for shorter pipes as a result.

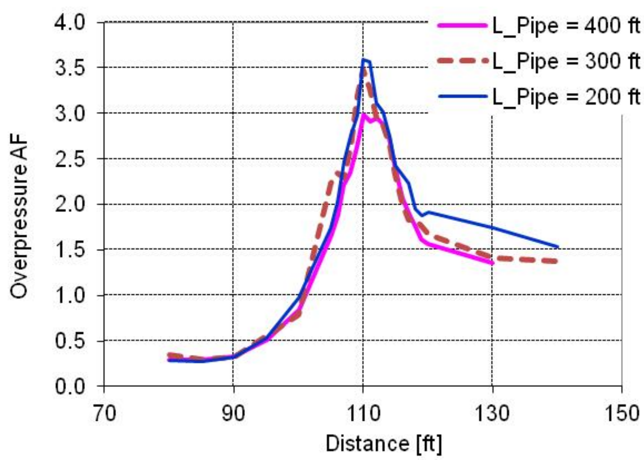

FIGURE 8. DEPENDANCE OF PRESSURE ADJUSTMENT FACTORS ON PIPE LENGTH (CASE 11)

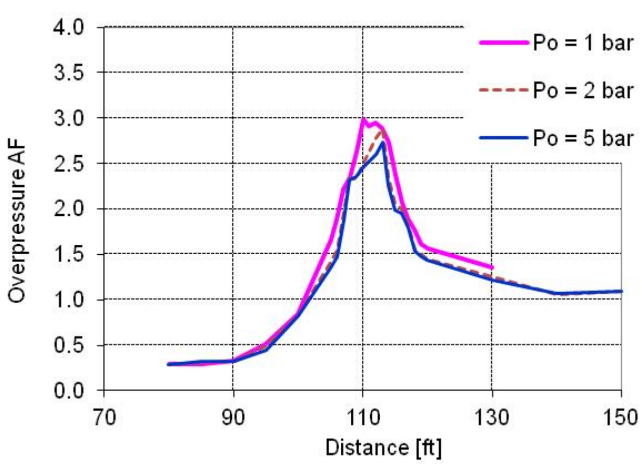

FIGURE 9. DEPENDANCE OF PRESSURE ADJUSTMENT FACTORS ON INITIAL PRESSURE (CASE 11, 400 FT PIPE)

Influence of Initial Pressure

Figure 9 depicts the dependence of the overpressure AF on initial pressure for initial pressures of 1 bar to 5 bar. The flame acceleration rate of Case 11 and a 400 foot pipe length were employed for this comparison. The initial pressure exerts a relatively small influence on the overpressure AF, with higher initial pressures decreasing the AF. Doubling the initial pressure from 1 bar to 2 bar decreases the overpressure AF by about 0.2. It should be noted that a constant reaction rate was implicitly assumed for this comparison (i.e., the flame acceleration rate was held constant), whereas the reaction rate would actually be a function of initial pressure.

Influence of Initial Fuel Concentration Distribution

Figure 10 shows the dependence of the overpressure AF on the initial fuel concentration distribution for Case 11 with a 400 ft long pipe. A fuel concentration distribution from 0 ft to 80 ft was characterized as a linear energy distribution from 0 up to the maximum stoichiometric-equivalent value. It should be noted that the DDT is still assumed to occur at 110 ft so that there is still a 30 ft long stoichiometric mixture ahead of the location where the DDT occurs.

As expected, a fuel concentration distribution ahead of the DDT onset reduces the overpressure AF significantly relative to that for a uniform (i.e., constant) stoichiometric concentration. The fuel concentration distribution (i.e., the released energy distribution) results in a weaker expansion of burned gas. The resulting gas pressure increment is smaller than that for the constant stoichiometric mixture. The DDT overshoot pressure is therefore reduced, compared to that for the constant stoichiometric mixture.

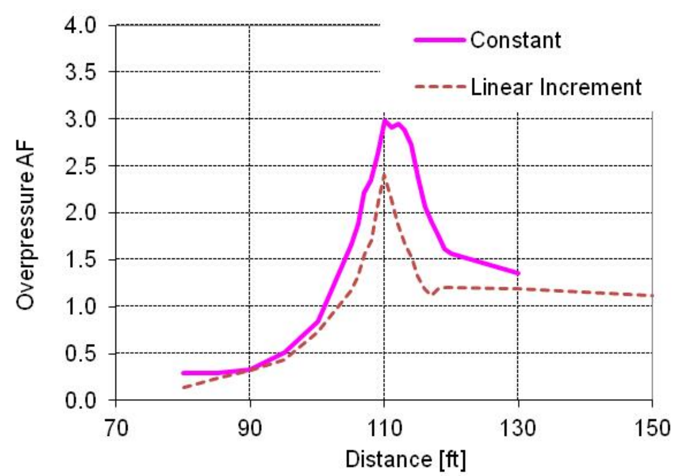

FIGURE 10. DEPENDANCE OF PRESSURE ADJUSTMENT FACTORS ON INITIAL PRESSURE (CASE 11, 400 FT PIPE)

CONCLUSIONS

The following conclusions are drawn based on results of this evaluation:

1) The region where the overpressure for a DDT is markedly higher than that for a steady-state detonation wave is localized. However, within this region, it was found that the overpressure can be up to a factor of 3.5 higher than that for a steady-state detonation wave for the range of parameters examined in this analysis.
2) All of the fast acceleration rate cases yielded similar overpressure adjustment factors, regardless of the time required for the flame front to reach the location where the DDT occurs.
3) The fast acceleration rate cases yielded higher overpressure adjustment factors relative to that for the slow acceleration rate case. Hence, the critical parameter with respect to flame acceleration is the acceleration near the location where the DDT occurs. The DDT overpressure is relatively insensitive to the earlier portion of the flame acceleration history.
4) The overpressure adjustment factors increases with decreased pipe length. Decreasing the pipe length by a factor of 2 increased the adjustment factor by 0.5.
5) The overpressure adjustment factors decreases with initial pressure, but the effect is not large. Doubling the initial pressure only decreased the adjustment factor by 0.2.
6) Accounting for an initial fuel concentration distribution decreases the overpressure adjustment factor significantly relative to that for a uniform stoichiometric mixture.

The impulse adjustment factor was not evaluated in this work. It is recommended that this should be examined as part of future work.

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