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Comparison of average radial expansion velocity from impacted liquid filled cylinders

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Abstract

In this paper, the average radial expansion velocity of an impacted fluid filled cylindrical target is investigated. Theoretical and numerical predictions of the radial expansion velocity are compared to the experimentally measured radial expansion velocity. The primary objective of this work is to assess the ability of these theoretical and numerical techniques to predict the radial expansion velocity. A secondary objective of this work is to quantify the effect of changes in dimensional scale on the radial expansion velocity and to construct a simple physics based model which incorporates these scaling effects. Two-dimensional numerical hydrocode simulations accurately predict the measured ejection velocity for tests with low projectile–target misalignment. However, three-dimensional numerical calculations, which account for this misalignment, accurately predict all experimental tests. A theoretical formulation, based on a simple conservation of energy principle, yields a zero-dimensional model which accurately predicts the two-dimensional hydrocode simulations. Thus for experimental simulations which have low projectile–target misalignment, the simple theoretical model developed here accurately predicts the average radial expansion velocity. A dimensional analysis of this theoretical formulation yields a scaling relationship which accurately predicts the effect of dimensional scale between two different experimental test series.

Keywords: Liquid dispersion; CTH; Scale model

1. Introduction

The underlying objective behind this work is to develop an understanding of the fluid breakup mechanisms and to predict the resulting drop size distribution and velocity distribution from a fluid-filled right circular cylinder after it has been impacted by a fast moving projectile. Understanding and predicting the long time dynamic evolution process of an impact loaded liquid system is a challenging hydrodynamic stability problem and will not be addressed here. However, as a first step towards understanding this complicated fluid breakup mechanism, developing an understanding of the fluid impact dynamics and the resulting ejection process is a

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key component of the underlying objective and is the focus of the work presented in this paper. To this end, the primary objective of this work is to assess the ability of hydrocodes and/or simple physics based models to accurately predict the initial impact and ejection of a fluid from a right circular cylinder. A secondary objective of this work is to develop a simple theoretical model which provides insight into the effect of changing the dimensional scale of the test.

There are several aspects of the fluid regime investigated here which are unique relative to classic shock loaded hydrodynamic phenomenology and hydrodynamic stability. First, the mixed time scales involved in the fluid evolution causes theoretical and experimental difficulty. The impact loading and resultant shock event occur on a microsecond time scale, whereas the fluid expansion, evolution and eventual droplet breakup processes occur on the millisecond time scale. Order of magnitude differences in the time scales for these two related events are increased as the ambient pressure is decreased. The early time scale shock pressure and velocity resulting from impact can be accurately predicted using hydrodynamic calculations. Thus the early time evolution is well understood. However, the difficulty arises when predicting the long time scale fluid dynamics which includes the eventual liquid breakup and resulting drop distribution. The fluid ejection process, which is the focus of the work presented here, represents the transition from the early or shock velocity time scale to the late time or expansion velocity time scale. In the context of hydrodynamic stability investigation, a difficult aspect of the work presented here is that there are no imposed disturbances. Disturbances are imposed by the fracture of the thin steel target membrane which initially contains the fluid. Thus predicting the final state time and length scales is more challenging.

The second aspect to this investigation which is unique is that all of the experiments presented here were conducted in a vacuum tank, approximately 1 Torr. This minimizes the effects of the ambient air, drives the Atwood number [1,2] to unity and delays the onset of instability growth. The Atwood number is defined as the ratio of density differences between the upper and lower fluids divided by the sum of the two densities, $A = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$. Together the various aspects of this work: impact loaded, no imposed disturbances and Atwood number near unity, define the regime investigated here within the larger context of classic hydrodynamic stability.

2. Background

Much work has been conducted in the field of hypervelocity liquid–solid impact phenomenology. During the early days of space exploration and continuing on today there has been a keen interest in the damage to liquid or gas filled fuel tanks by either orbital debris or micro-meteors [3–5]. A thirty year review of this work was published in a two part series which concluded in the development of a classification scheme of tank damage [6,7]. The orbital debris problem has led to the development of techniques to mitigate this damage mechanism and to develop models to characterize the impact, penetration and damage [8]. On the other end of the spectrum, there is also a large body of work concerned with the impact of a single droplet on a solid structure [9] or a liquid jet on a solid surface [10,11]. More specific to this investigation, much work has been done towards developing an understanding of a bulk fluid being impacted by a solid projectile and the resulting cavity formation and fluid ejection processes [12–15]. Understanding the resulting dynamics associated with a blunt body impact in a fluid or an underwater explosion have been a long standing problem in fluid mechanics [16]. As a variation of this classic work, the geometry investigated here is a finite quantity of fluid contained in a right circular cylinder impacted by a high velocity spherical projectile. Instead of the cavity dynamics including, growth and collapse, here the interest is in the cavity formation and the fluid ejection from the impacted cylinder. A simple kinetic energy approach to describe the radial expansion of fragments and expanding gases was developed by Gurney for predicting behavior of ordnance [17]. This model quickly estimates the resulting ordnance fragment velocity. In the Gurney model the energy of the explosion, i.e. the input energy into the system, is described with the Gurney velocity coefficient. Similar models have successfully coupled a conservation of energy formulation and a momentum balance to predict the penetration and cavity formation in high-speed water entry [18,19]. For the model developed here these same basic ideas are applied to a finite liquid system. The model developed here can be used to quickly assess the resulting ejected water velocity. With the additional aid of three-dimensional hydrocode simulations providing an