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Suppression of vortex shedding and its mitigation effect in gas explosions: an experimental study

H. Hisken [a, b, *], G.A. Enstad [b], V.D. Narasimhamurthy [b, c]

[a] Department of Physics and Technology, University of Bergen, Allégaten 55, 5007, Bergen, Norway
[b] Gexcon AS, Research and Development, P.O. Box 6015, NO-5892, Bergen, Norway
[c] Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai, 600036, India

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ABSTRACT

This paper reports occurrence of vortex shedding behind bluff-bodies in gas explosions, methods to suppress them using passive flow control techniques, and their overall impact on explosion overpressures. The pressure-time histories from a series of explosion tests, using an initially quiescent propane-air mixture in a vented channel of dimensions 1.5 m × 0.28 m × 0.3 m, are presented. Selected high-speed video frames visualizing the flame propagation are also presented. Three different bluff-obstruction scenarios are considered: 1) a reference case with a single smooth circular cylinder of diameter $D = 0.0157$ m, 2) a single cylinder identical to that in the reference case, mounted with a splitter plate of varying length from 5.13D to 0.26D, width 17.8D and thickness 0.06D, and 3) a single helically wired cylinder with wire diameter 0.1D and pitch 4D or 8D. All circular cylinders had a length of 17.8D and were mounted normal to the direction of the flow, spanning the channel cross-section 0.5 m downstream of the ignition point. The obstructions were inserted in the rig using a unique experimental setup. The peak overpressure generated by the explosion is of main interest. Both vortex shedding suppression techniques 2) and 3) yielded significant reduction in maximum overpressures when compared to the reference cylinder case 1). While all splitter plate configurations successfully reduced the maximum explosion overpressure, the splitter plates with length 1.02D and 0.51D were the most efficient, with an average reduction in overpressure of 32 ± 3%. The helical steel wire configurations also had a significant effect, with 25 ± 3% and 20 ± 3% reduction in the maximum overpressure for pitch 4D and 8D, respectively. The high-speed video visualization further buttressed the quantitative findings in the pressure measurements and clearly showed vortex shedding suppression. The current observations imply that the contribution from vortex shedding, i.e. apart from turbulence effects, to the overpressure generation in gas explosions is significant. The modelling community must consider this while preparing their simulators.

1. Introduction

The industries associated with energy extraction and conversion often involve the handling and storage of large quantities of flammable gases or liquids. Gas or vapour cloud explosions following an accidental release of a flammable gas or liquid may cause fatalities and severe material and environmental damage – examples are Piper Alpha (July 6, 1988), Buncefield (December 11, 2005), Deepwater Horizon (April 20, 2010), and Fukushima Daiichi (March 11, 2011) (Marsh, 2014; Skjold et al., 2014). Industrial-scale gas explosions generally involve premixed combustion embedded in unsteady, turbulent flows in complex geometries. The interplay between turbulence and premixed combustion depends on the characteristic time and length scales of turbulence relative to those of the chemical reactions. Vortices of sufficient strength increase the overall flame surface area, promote mixing and heat transfer, leading to higher mass burning rates in the propagating flame brush, see e.g. (Damköhler, 1940; Spalding, 1971; Libby et al., 1979; Peters, 1988). The primary mechanism for flame acceleration in congested geometries is the positive feedback between the expansion of combustion products, turbulence generated in the

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* Corresponding author. Gexcon AS, Research and Development, Fantoftveien 38, P.O. Box 6015, NO-5892, Bergen, Norway.
E-mail addresses: Helene.Hisken@gexcon.com (H. Hisken), Gisle.Enstad@gexcon.com (G.A. Enstad), vagesh@iitm.ac.in (V.D. Narasimhamurthy).

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unreacted mixture downstream of the propagating flame front, especially in shear- and boundary-layers from flow past obstacles and walls, and enhanced combustion rates (Wheeler, 1919; Shchelkin, 1940; Moen et al., 1980, 1982). Rapid flame acceleration creates pressure waves that can potentially damage structures; therefore, the severity of an explosion is usually given in terms of the generated overpressure, its spatial distribution, and the associated pressure impulse.

The process industries invest considerable resources in reducing the probability and consequences of a potential accident; the latter can be addressed by applying appropriate mitigation measures (Eckhoff, 2005). In order to reduce the gas explosion hazard, it is crucial to have detailed knowledge of the physical phenomena leading to flame acceleration. This is particularly important when developing engineering software for consequence prediction of industrial scale explosions. For computational fluid dynamics (CFD) software used to simulate large-scale gas explosions in complex geometries, phenomenological or empirical sub-grid models are implemented to represent processes that are not resolved on the computational grid. For example, such CFD models must account for turbulence production by sub-grid scale obstructions (Skjold et al., 2014). Other than turbulence, a range of fluid flow instabilities, either intrinsic in nature or induced by the surrounding geometry, may also promote flame acceleration in gas explosions (Ciccarelli and Dorofeev, 2008). For a certain range of Reynolds numbers, the Bénard–von Kármán (BVK) instability, resulting in the phenomenon called *vortex shedding*, occurs in non-reacting bluff-body wake flows (Zdravkovich, 1997). The BVK instability introduces a strong periodicity in the velocity and pressure measurements just downstream of the bluff-body, and is associated with a significant increase in the form drag, enhanced mixing, as well as possible structural vibrations and noise. Therefore, a range of engineering techniques to suppress or control vortex shedding has been developed (Choi et al., 2008; Zdravkovich, 1997).

The BVK instability and its effects have been extensively studied for non-reacting flow (Roshko, 1993; Williamson, 1996), and in reacting flow for flame holder configurations in various combustor applications (Hertzberg et al., 1991; Fureby, 2000; Lieuwen, 2013). Some investigators (Kong, 1996; Kong and Sand, 1996) measured and discussed vortex shedding in transient, explosion driven flow past various bluff-bodies. However, to the present authors' knowledge, no information is available on the effect of applying control methods to bluff-bodies in gas explosions. This experimental study investigates the occurrence of vortex shedding behind a single circular cylinder embedded in a premixed fuel-air cloud during a gas explosion, ways to control the shedding, and finally its overall impact on the overpressure generation.

2. Theory and background

2.1. Flow around a circular cylinder

The circular cylinder is a canonical object in practical applications and has been widely studied in the field of fluid mechanics (Roshko, 1993; Zdravkovich, 1997, 2003). For flow across a circular cylinder, the Reynolds number is defined as $Re = UD/\nu$, where U is the upstream flow speed, D is the diameter of the cylinder, and ν is the kinematic viscosity of the fluid. The two-dimensional flow around a circular cylinder can be represented by a thin viscous boundary-layer, surrounded by an external potential flow. Upstream of the highest point of the curved body, where the streamlines converge, the pressure gradient is *favourable*, i.e. it points in the opposite direction of the flow. However, downstream of the highest point of the curved body the streamlines diverge, giving rise to a positive pressure gradient with respect to the flow direction, i.e. an *adverse* pressure gradient. The boundary-layer experiences the same pressure as the external flow. If the adverse pressure gradient is sufficiently strong, the flow near the wall will decelerate faster than the external flow, and eventually reverses its direction leading to boundary-layer separation.

Following flow separation, shear layers emanate from each side of the bluff-body. At Re from ~4 to 47, the separated shear-layers roll up to form two counter-rotating steady laminar vortices behind the circular cylinder. When Re exceeds ~47, the two-dimensional wake becomes globally unstable and unsteady. The BVK instability is initially observed as a periodic oscillation of the laminar wake, producing two staggered rows of counter-rotating vortices in an anti-symmetric pattern. Regions of concentrated vorticity are then *shed* periodically from alternate sides of the cylinder and convected downstream, forming a *von Kármán vortex street*. The vortex shedding is nominally two-dimensional in nature for $Re < 190$. At $Re \approx 190$, three-dimensional effects due to intrinsic secondary instabilities becomes appreciable (Williamson, 1996). The periodic oscillations persist, albeit with less coherence, as Re increases, and the three-dimensional structures become increasingly disordered. At $Re > 1200$, vortices generated by the convective Kelvin–Helmholtz instability in the separated shear layers start to appear (Bloor, 1964). The turbulence transition point in the shear layers move upstream towards the cylinder with increasing Re (Schiller and Linke, 1933). The boundary-layer around the circular cylinder itself undergoes transition to turbulence at $Re \approx 200{,}000$. The more energetic turbulent boundary-layer can resist the adverse pressure gradient and hence separation for a longer time than the laminar boundary-layer. Consequently, the boundary-layer transition leads to less pressure deficiency across the cylinder, i.e. less *form drag*, and a narrower wake (Roshko, 1993). However, for $Re > 200{,}000$, coherent vortex shedding can still be discerned (e.g. Thomann, 1959; Roshko, 1961; Williamson, 1996; Rodríguez et al., 2015).

2.2. Flow control methods

The flow oscillations due to two-dimensional vortex shedding can be characterized by the Strouhal number $St = fD/U$, where f is the shedding frequency. For a circular cylinder, St can be expressed as a piecewise linear function of $1/\sqrt{Re}$ in the flow regimes from $47 < Re < 2 \times 10^5$ (Fey et al., 1998). Based on these relations, St varies between 0.18 and 0.21 for $1000 < Re < 2 \times 10^5$. As vortices shed alternately from each side of the cylinder in a counter-rotating fashion, they produce a lateral force on the cylinder. For flow past real structures, this may cause damaging vortex-induced vibrations (VIV) if the shedding has some critical frequency close to the natural frequency of the structure (i.e. the so-called *lock-in* phenomenon). Overall, the onset of vortex shedding is associated with a significant increase in the form drag, enhanced mixing, as well as possible structural vibrations and noise. Therefore, several engineering techniques to eliminate or suppress vortex shedding have been developed, and are applied for structures such as oil-rigs and suspension bridges.

Flow control methods for bluff-body wakes can be either *passive* or *active* (Choi et al., 2008). The present study focuses on passive control methods, as they do not require any power input or feedback sensor, and therefore are straightforward to implement. In particular, the methods for controlling bluff-body wake flows considered here entail direct modification of either (i) the near-wake or (ii) the boundary-layer. A classical type (i) method is to introduce a thin splitter plate along the wake centre-line at the base region downstream of the cylinder, as illustrated in Fig. 1. A splitter plate prevents the two separated shear layers from interacting, and thus stabilizes the near-wake (Roshko, 1993).