CHEMICAL ENGINEERING TRANSACTIONS
VOL. 77, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216

DOI: 10.3303/CET1977030

On the Occurrence of Flame Instabilities during Dust Explosions

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Flame instabilities are well-known phenomena during gas explosions. Numerous publications address intrinsic flame instabilities, Raleigh-Taylor instabilities, thermal–diffusive instabilities and acoustically driven flame instabilities the latter is especially known to affect vented gas explosions. For dust explosions flame instabilities are not considered to play an important role due the intrinsic turbulence being present and therefore overriding any flame instabilities.
The present paper however, addresses two series of experiments where flame instabilities have been observed which affect the course of dust explosions. This has never been recognised or reported upon before. It is important to understand these phenomena in order to be able to predict under which conditions they occur and exactly how they affect the course of explosions.

1. Introduction

The first series of experiments where flame instabilities during dust explosions were observed concern the testing of explosion isolation devices and especially explosion isolation flap valves. Isolation devices reduce the risk of dust explosions propagating from a process vessel protected by explosion venting, explosion suppression or containment into connected equipment. During tests involving vessels protected by explosion venting the closing of isolation valves led to considerable and unexpected increases of observed explosion pressures in the process vessel. The current paper explains how flame instabilities are responsible for this phenomenon.
The second series of experiments concern dust explosion experiments in a 55m^3 closed vessel. During these experiments acoustically driven flame instabilities were observed which increased combustion rates. The current paper discusses the flame instability and attempts to reduce its impact during explosion experiments.

2. Flame instabilities

Flame instabilities cause increased combustion rates and are especially known to influence laminar flames. However, also turbulent flames may be affected by similar mechanisms (Boughanem, 1998). Generally, it is expected that the turbulence overrides the effects of flame instabilities. Laminar flames are known to be unstable: The most well-known instability mechanisms are the hydrodynamic Darrieus–Landau instability caused by the gas expansion effect, the Raleigh-Taylor instability caused by buoyancy effects and the diffusive-thermal instability caused by molecular diffusion effects. Figure 1 shows sequences of a Raleigh-Taylor instability developing in a vented 1.5 m^3 chamber.
The Richtmyer-Meshkov flame instability is a variation of the Raleigh-Taylor instability and occurs when shock waves or pressure waves interact with the flame. When the shock or pressure wave accelerates the flame in the direction of the heavier unburned flammable mixture the flame becomes unstable causing an increase of the flame surface area.

Paper Received: 5 December 2018; Revised: 13 May 2019; Accepted: 1 July 2019

Please cite this article as: van Wingerden K., Wilkins B., van Wingerden M., Holme M., Schepp P., Lade R., 2019, On the occurrence of flame instabilities during dust explosions, Chemical Engineering Transactions, 77, 175-180 DOI:10.3303/CET1977030

Figure 1: Example of a Raleigh-Taylor instability developing in a 1.5 m^3 vented chamber (stoichiometric hexane- air). Top left: vent opens, flame surface drawn in direction of vent opening (towards the bottom right) and stabilises. Top right: pressure in chamber close to atmospheric. Flame starts to accelerate into chamber towards heavier unburned vapour-air mixture. Bottom left: Raleigh-Taylor instability causes large flame evolutions on flame surface causing further flame accelerations. Bottom right: development of flame evolutions continues.

An acoustically driven flame instability is also a variation of the Richtmyer-Meshkov instability. A standing acoustic wave in a vessel causes a fire ball to be accelerated alternatingly in two directions. The flame is stabilised at one end and destabilised at the other end -depending on whether the acceleration is directed to the burned or unburned fluid. An increased energy release rate by an accelerating flame is causing the standing acoustic wave to become stronger and stronger. Acoustically driven flame instabilities are well-known phenomena during vented gas explosions. An example is shown in Figure 2.

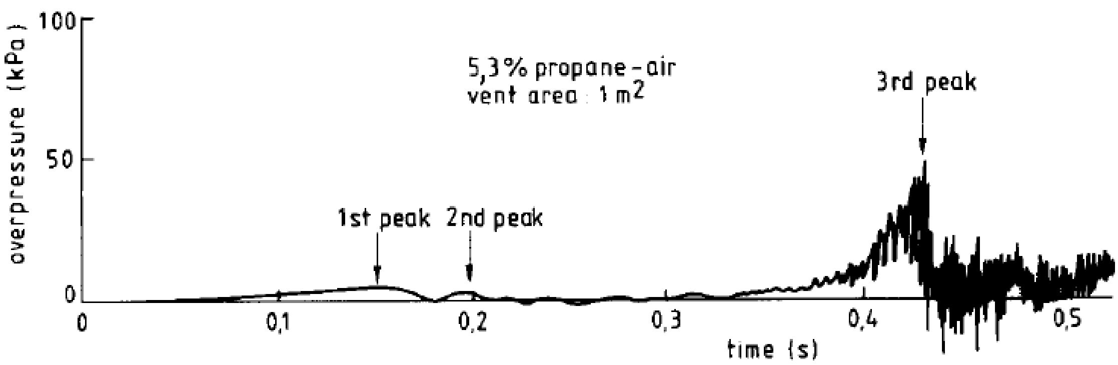

Figure 2: Example of an acoustically driven flame instability occurring in a vented 5.2 m^3 vessel. A 5.3 % propane-air mixture was ignited. The acoustically driven instability is developing during what has been indicated as the third peak and recognisable by the acoustic wave superposed on the pressure-time history (van Wingerden, 1983).

3. Flame instabilities occurring during testing of explosion isolation devices

Sippel, 2016 and Schepp, 2017 report on experiments where explosion isolation systems are tested and especially explosion isolation valves. In all of these experiments explosion venting was applied to the source vessel. Figure 3 shows examples of pressure-time histories seen in maize starch (K_{St} = 200 bar.m.s^{-1}, p_{max} = 9 bar) dust explosion tests performed in a vented 10 m^3 vessel connected to an 800 mm diameter, 6 m long pipe. The vent opening size measured 0.5 m^2. The explosion vent opened at a pressure of 100 mbar. Tests were performed with the 800 mm pipe being open, without the pipe connected (blind flange) and with an explosion isolation flap valve installed in the 800 mm pipe at 6 m from the vessel. Explosion overpressures seen with an open pipe are generally somewhat lower than when no pipe is mounted since the pipe opening adds to the total venting area available. When the flap valve is installed the pressure-time history initially follows the pressure of the open pipe tests. Just before the valve closes completely the pressure starts increasing. In this particular experiment the pressure increases sharply and reaches a value 4.4 times higher than without a flap valve installed in the pipe and 2.4 times higher than the pressure without a pipe connected to the vessel. The pressure pulse duration inside the vessel is also considerably longer when a flap valve is used. Whilst these increases in pressure in the source vessel are often observed their magnitude is rather variable.

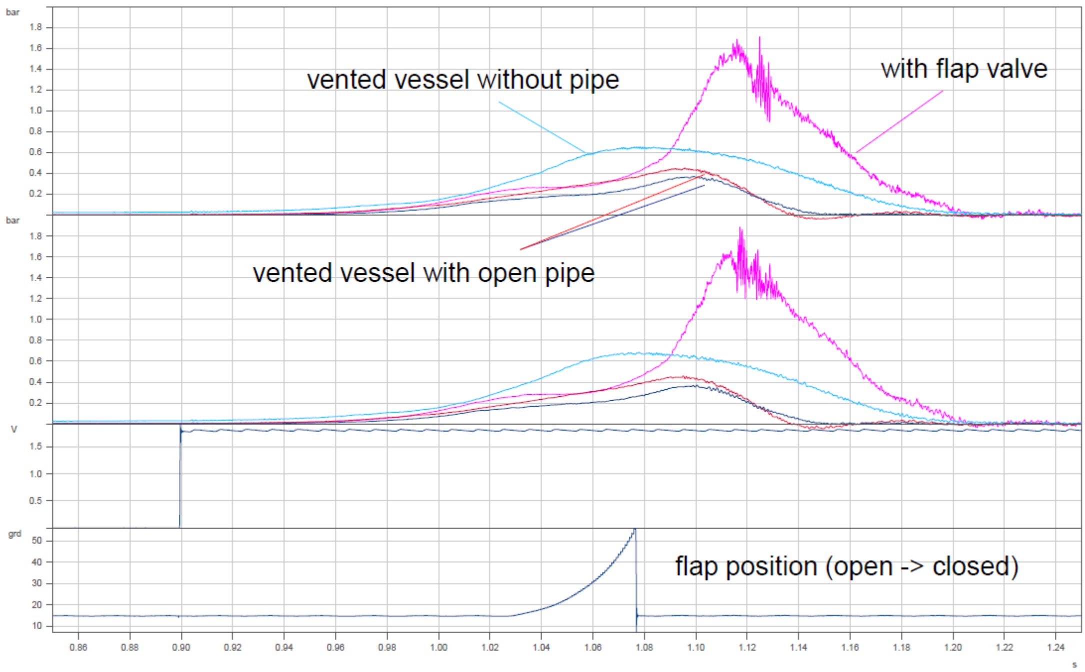

Figure 3: Strong increase of overpressures seen during tests applying a combination of explosion venting and explosion isolation using explosion isolation flap valves. The pressure-time histories concern tests performed in a 10 m^3 vessel provided with 0.5 m^2 vent opening. Tests were performed with an explosion flap valve installed in an 800 mm pipe connected to the vessel, but also without the valve installed and without the pipe connected to the vessel (Sippel, 2016). Pressure-time histories are shown at two different locations in the vessel (top figure and second from top figure). The third from top figure shows the moment of ignition whereas the bottom figure shows the closing of the explosion isolation flap valve.

Sippel, 2016 explain the pressure increases seen by the interaction of the shock wave caused by the closing of the valve, with the flame in the 800 mm pipe line and by the turbulence generated by the closing valve and its effect on the combustion. These effects are influencing flame propagation only locally. It is however more likely that the sudden closing of the valve causes a change in the flow pattern in the vessel resulting in an acceleration of the flame towards the vent opening potentially causing a Raleigh-Taylor instability exactly as shown and described in Figure 1. The influence of a Raleigh-Taylor instability will be stronger during vented explosions than in fully closed vessels. Here it should be mentioned that the described increase of combustion rates was never recognised during explosion isolation valve functionality tests in fully closed vessels. Hence this is an indication that Raleigh-Taylor flame instabilities could play a role.
Alternatively, or additionally the shock/pressure wave generated by the closing of the valve could have caused a Richtmyer-Meshkov flame instability also causing the flame to accelerate towards the denser unburned dust-

air mixture when exiting from the pipe. Flame instability would explain the considerable pressure increase as it is a global effect, affecting combustion over a large part of the flame surface (as shown in Figure 1). Flame instabilities would also be a possible explanation of why the observed pressures are sometimes increasing when the isolation device is located further away from the source vessel (higher internal pressure causing stronger flame accelerations in the opposite direction when the flame is suddenly drawn towards the vent opening; a stronger shock wave is generated at the valve returning towards the flame) (Schepp, 2017). It also explains why the effects are stronger at lower initial turbulence levels as reported by Schepp, 2017. According to Boughanem, 1998, flame instability influences in turbulent flows increase for small values of the ratio of turbulence intensity divided by the laminar flame speed and large values of the ratio of integral length scale divided by the laminar flame thickness, supporting this observation. The exact configuration of vent, pipe and valve will determine how strong the effect of flame instabilities on the subsequent flame propagation process will be.

4. Flame instabilities in a large elongated explosion vessel

Dust explosion experiments performed in a 55 m^3 elongated vessel (L/D=4.5) also seem to be affected by flame instabilities. The vessel is shown in Figure 4. One end of the vessel is provided with a flat end plate whereas the other end is hemispherical. Dust is injected from a series of bottles mounted onto one of the long sides of the vessel.

Figure 4: 55 m^3 elongated vessel provided with 8 dust injection bottles.

Closed vessel experiments were performed using maize starch (K_{St}=165 bar.m.s^{-1}, p_{max}=8.6 bar) as a fuel. Central ignition was achieved using two Sobbe 5kJ igniters. An example of the results obtained are shown in Figure 5. Oscillations due to a standing wave in the vessel are superposed onto the pressure-time history. The pressure maxima of the oscillations are increasing up to the moment of reaching the maximum overpressure indicating the positive feedback mechanism with the combustion as is typical for acoustically driven flame instabilities. To verify the occurrence of acoustically driven instabilities further experiments were conducted where the ends of the vessel were covered with rock wool to partially damp the standing wave. Results are shown in Figure 5 comparing the original pressure-time history with those having the vessel ends covered with one and two layers of rockwool respectively. As can be seen the amplitudes of the oscillations superposed on the pressure time histories are lower, the rates of pressure rise are lower and the maximum overpressures have also decreased all indicating a less strong influence of the flame instability.

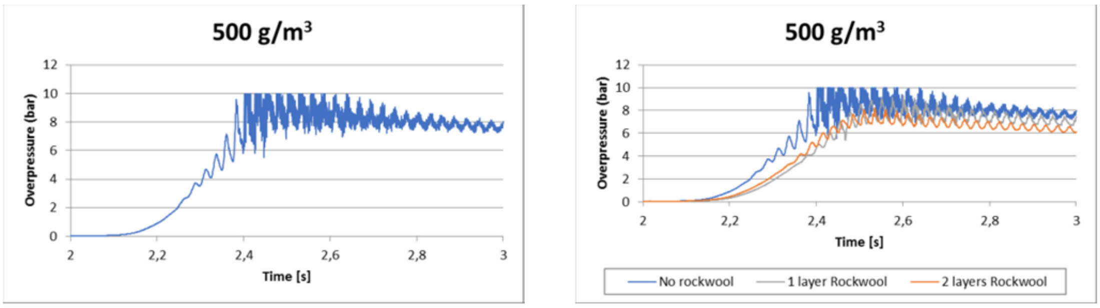

Figure 5: Effect of rockwool on 500 g/m^3 closed vessel maize starch explosions in 55 m^3 elongated vessel.

Increasing the dust concentration would also lead to more damping decreasing the influence of acoustically driven flame instabilities. This is shown in Figure 6 for explosions in 500, 650 and 750 g/m^3 maize starch-air mixtures. In spite of being more reactive the rate of pressure rise for the three mixtures is comparable due to the stronger influence of the acoustically driven instability seen for the less reactive 500 g/m^3 mixture. For this mixture the amplitudes of the oscillations are considerably higher indicating the stronger coupling between standing wave and combustion.

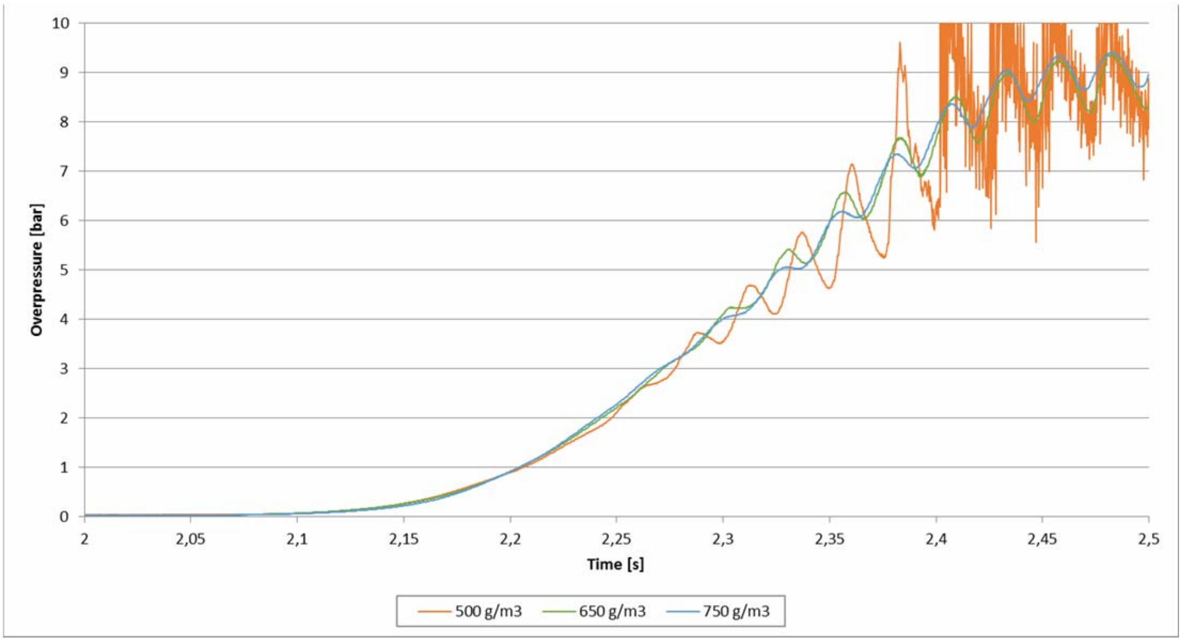

Figure 6: Effect of dust concentration on the occurrence and strength of acoustically driven flame instabilities.

Acoustically driven flame instabilities may also affect vented explosions in large vessels. Oscillations superposed on pressure-time histories measured during dust explosion tests in a slender silo reported by Eckhoff, 1987 indicate this possibility.

5. Discussion

In spite of the turbulence and presence of dust flame instabilities, Raleigh-Taylor instabilities and Richtmyer- Meshkov instabilities (or acoustically driven flame instabilities) can occur during dust explosions. According to a numerical study performed by Boughanem, 1998 flame instabilities in turbulent mixtures can occur for the following conditions:

1. small values of the ratio of turbulence intensity divided by the laminar flame speed

2. large values of the ratio of integral length scale divided by the laminar flame thickness
3. large heat release values
4. large positive values of the flame Richardson number Ri (Ri is positive when the flow acceleration is directed from the fresh mixture to the burnt gas)
5. small values (below one) of the flame Lewis number Le.

For low turbulence conditions at large scale the first two conditions are met and these were most likely met in the experiments described. Richtmyer-Meshkov instabilities occur for negative values of Ri and have shown to give dramatic increases of combustion rates (see e.g. Thomas, 2001). Positive values of Ri occur when the shock waves reflect at the walls and hit the flame again. Also here considerable flame accelerations are possible (see e.g. La Fléche, 2017). This is the case for acoustically driven flame instabilities where alternatively positive and negative values of Ri occur depending on the direction of the acoustic pressure wave.
The occurrence of large heat release values and the small value of the Lewis number, Le, cannot be judged for the dusts in question. Nevertheless, the numerical study performed by Bourghanem, 1998 indicates that at least on industrial scale conditions these can be met allowing for the occurrence of flame instabilities during dust explosions. The described experiments support this.
Recognising the possible occurrence of flame instabilities allows these to be taken into account during the design of dust processing equipment:

- Higher combustion rates due to flame instabilities implying e.g. choice of larger vent openings to counteract the higher explosion pressure generated
- Avoidance of occurrence of flame instabilities by design: choice of location of connecting ducts, choice of angle of walls of protected enclosure, choice of isolation device

6. Conclusions

Two series of dust explosion experiments are discussed during which the combustion rates are most likely increased due to flame instabilities. The first set of experiments concern the use of explosion isolation valves where the sudden closing of the valve causes a pressure / shock wave to run back into the protected vessel resulting in a Richtmyer-Meshkov instability or Raleigh-Taylor instability causing increased combustion rates and therefore considerably higher overpressures (in particular for vented explosions). The second series of experiments concern closed vessel explosion in an elongated vessel where acoustically driven flame instabilities occur and consequently increase the combustion rates and thereby the observed rates of pressure rise.
Research is needed to understand conditions for occurrence of flame instabilities during dust explosions, the extent of possible increases of combustion rates and possible remedies.

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