Experimental investigation of flame propagation in turbulent propane-air mixtures and dust-air suspensions

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1 Introduction

Dust explosions pose a hazard whenever a sufficient amount of combustible material is present as fine powder, the powder can be dispersed in air to form an explosive dust-air suspension within a sufficiently confined volume, and there is an ignition source present. Detailed modelling of industrial dust and gas explosions from first principles is a formidable task, and current methods for mitigating the effects of industrial explosions therefore rely on empirical correlations. Recent efforts towards simulating the course of dust explosions by combining computational fluid dynamics (CFD) and correlations for turbulent burning velocity have produced promising results [1-2]. However, the current models do not account for the inherent differences between gaseous fuel-air mixtures and dust-air suspensions. Combustion parameters for dust clouds are typically derived from standardized tests in constant volume explosion vessels, and it is not straightforward to derive correlations between turbulent flow properties and the rate of combustion.

The work presented here is part of a strategic program where the goal is to develop an experimental framework for investigating turbulent flame propagation in dust-air suspensions [3-9]. The primary motivation is to gain improved understanding of the dust explosion phenomenon, and hence to be able to develop improved models for assessing explosion risks in the process industry. It is foreseen that future state-of-the-art risk assessments in the powder handling industry will involve the use of CFD.

The present contribution entails an experimental study of turbulent flame propagation in a 3.6 metre flame acceleration tube [3-6], and two types of combustible mixtures: propane-air mixtures and mechanical suspensions of maize starch and air. The experimental approach is similar to that of Pu *et al.* [10-11], but the tube used here is twice the length, has a quadratic rather than circular cross section, and is oriented horizontally instead of vertically. The main focus in the current study is to explore reliable and robust methods for detecting time of flame arrival in turbulent dust flames. The experimental procedure for tests with initially turbulent flow conditions is essentially the same for dust and gas explosions, and for gaseous fuels it was also possible to investigate initially quiescent mixtures. Only constant volume experiments are included here, since such tests are simple to perform and well suited for validating the methodology.

2 Experiments

The 3.6 metre flame acceleration tube consists of three 1.2 metre sections with internal cross-section 0.27 m × 0.27 m (Fig. 1). Tests can be performed with initial turbulence, generated by injecting air from three 2-litre pressurized reservoirs, or under initially quiescent conditions. The initial pressure in the reservoirs was 16.2 bar*g*, and the absolute pressure in the tube prior to injection was 0.6 bar*a*. For solid fuels, air from the high-pressure reservoirs dispersed the dust in three 0.9-litre pre-dispersion chambers before the dust was injected into the vessel through specially designed pepper-pot nozzles (Fig. 1). For gaseous fuels, the explosive mixture was prepared by evacuating the tube below 0.6 bar*a*, and adding gas while monitoring the pressure with a Druck 705 digital pressure indicator.

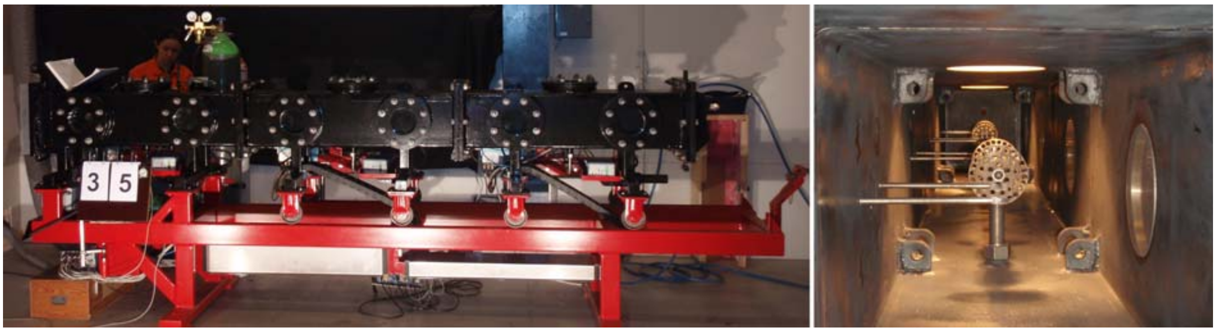

Figure 1. The 3.6 metre flame acceleration tube (left), and internal view of the tube showing flame probes, dispersion nozzles, brackets for fixing obstacles, and windows (right).

The ignition sources used in the present study were either an electric spark from a high voltage coil or a 1 kJ chemical igniter. The ignition source was positioned 0.3 m from the left end of the tube in Fig. 1, and chemical igniters were always pointed towards the closed end. An ignition delay of 1 s from onset of dispersion was used for all turbulent tests. The pressure development in each of the reservoirs and inside the tube was recorded with Kistler 701A piezoelectric pressure transducers and Kistler 5011 Charge Amplifiers.

A Phantom v210 digital high-speed video camera and ten temperature probes were used to measure flame propagation along the tube. The probes were made from 0.3 mm type K thermocouple wire, welded in an inert atmosphere, and mounted on rods (Fig. 1). There were two probes for each of the five windows downstream of the ignition location. The amplifiers for the thermocouple signals used one AD597 conditioner and set-point controller for each channel. Fig. 2 illustrates the procedure for identifying flame arrival times from temperature measurements, based on either the temperature T or its time derivative dT/dt after smoothing the data series [12]. The thresholds for the derivative criterion were typically set to a value in the range 400-2000 ^{o}C s^{-1}, depending on the amplitude of instantaneous fluctuations prior to the main rise. This approach proved quite efficient as a means of identifying the onset of rapid temperature rise. In addition to the derivative, three thresholds were investigated for the temperature criterion: 100, 200 and 300 ^{o}C (Fig. 2). However, the crossing trajectories for some of the temperature curves in Fig. 2 indicate an inherent limitation associated with this approach.

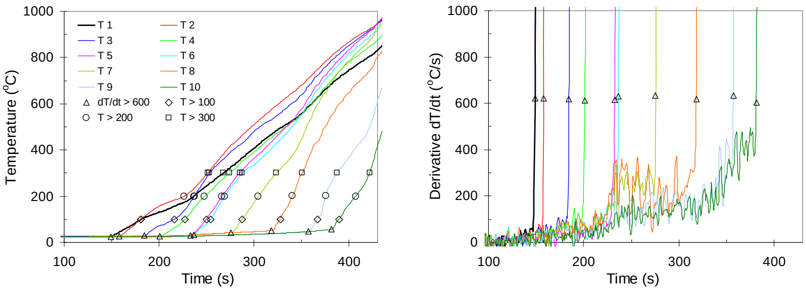

Figure 2. Temperatures (left) and time derivatives of temperatures (right) for test number 22: initially turbulent mixture of 6.0 % propane in air, ignited by an electric spark.

4 Results

Table 1 lists some of the experimental conditions covered in the present study, and Figs. 3 and 4 summarize the corresponding results. Initially turbulent propane-air mixtures ignited by 1 kJ chemical igniters have also been investigated, but these are described elsewhere [13]. Although the pressure-time histories differ significantly for the various mixtures and initial flow conditions, the results from repeated tests are reasonably consistent. The tests with dust resulted in two categories of results: flame propagation through the entire tube and high pressure (included in Table 1), or quenching resulting in low explosion pressures and layers of non-combusted dust inside the tube.

Table 1. Summary of test conditions for the experiments summarized in Figs. 3 and 4.

Initial conditions	Test no.		Concentration	Explosion pressure (bar*a*)	
Initially turbulent Spark ignition	7	13	3.0 vol % propane in air	6.17	5.66
	8	14	4.5 vol % propane in air	8.72	8.94
	9	15	6.0 vol % propane in air	7.45	7.34
	10	16	7.5 vol % propane in air	4.84	5.43
Initially quiescent Spark ignition	18	26	3.0 vol % propane in air	4.89	4.75
	20	28	4.5 vol % propane in air	8.02	7.88
	22	30	6.0 vol % propane in air	6.88	6.68
Initially turbulent Chemical igniter	50	53	500 g m^{-3} maize starch in air (nominal)	7.28	7.30

The flame arrival times based on data from the thermocouples differ significantly for the various criteria. The time derivative works reasonably well for identifying the onset of rapid temperature rise, but this typically occurs prior to visual detection of the flame front in the high-speed video recordings. For propane-air mixtures, the observations of visible flames coincide with a temperature rise in the thermocouples of 100-300 ^{o}C, depending on the reactivity of the mixture. Fig. 5 summarizes the delay between the detected onset of rapid temperature rise and the visual observation of the flame front for all propane-air tests. Figs. 6 and 7 show selected frames from video recordings. It was not straightforward to identify unambiguous flame arrival times from these pictures, especially for lean gaseous mixtures and dust flames (dust settled on the windows). Another complicating factor was the pulsating movement of the flame front when it propagated towards the far end of the tube.

5 Discussion and conclusions

The paper describes an experimental study aimed at developing reliable and accurate methods for detecting flame arrival times in turbulent dust-air suspensions. The present work focused on flame sensors built from 0.3 mm type K thermocouples. It was found that the probes typically detect onset of rapid temperature rise prior to arrival of the visible flame, but it was not straightforward to correlate the delay time between the measurements and the arrival of the visual flame front. This uncertainty may reduce the applicability of the method for flame propagation in dust clouds, where unambiguous detection of the visible flame front is limited due to light reflection from particles ahead of the flame front. It may be possible to reduce the diameter of the thermocouple wire, and hence reduce the response time of the temperature measurements. However, the probes should be reasonably robust in order to survive the dust dispersion process. Furthermore, as long as the main objective is flame detection, rather than actual temperature measurements, the present study suggests that the response time of the 0.3 mm thermocouples may be adequate.

Future work will focus on improving the methodology and exploring alternative measurement principles, such as ionization gauges or optical detection [5-6]. It is foreseen that experiments with ionization gauges may clarify the uncertainty associated with the apparent premature detection of rapid temperature rise obtained with the thermocouples, since the presence of ions may serve as a less ambiguous criteria of flame arrival, compared to the observation of a visible flame.

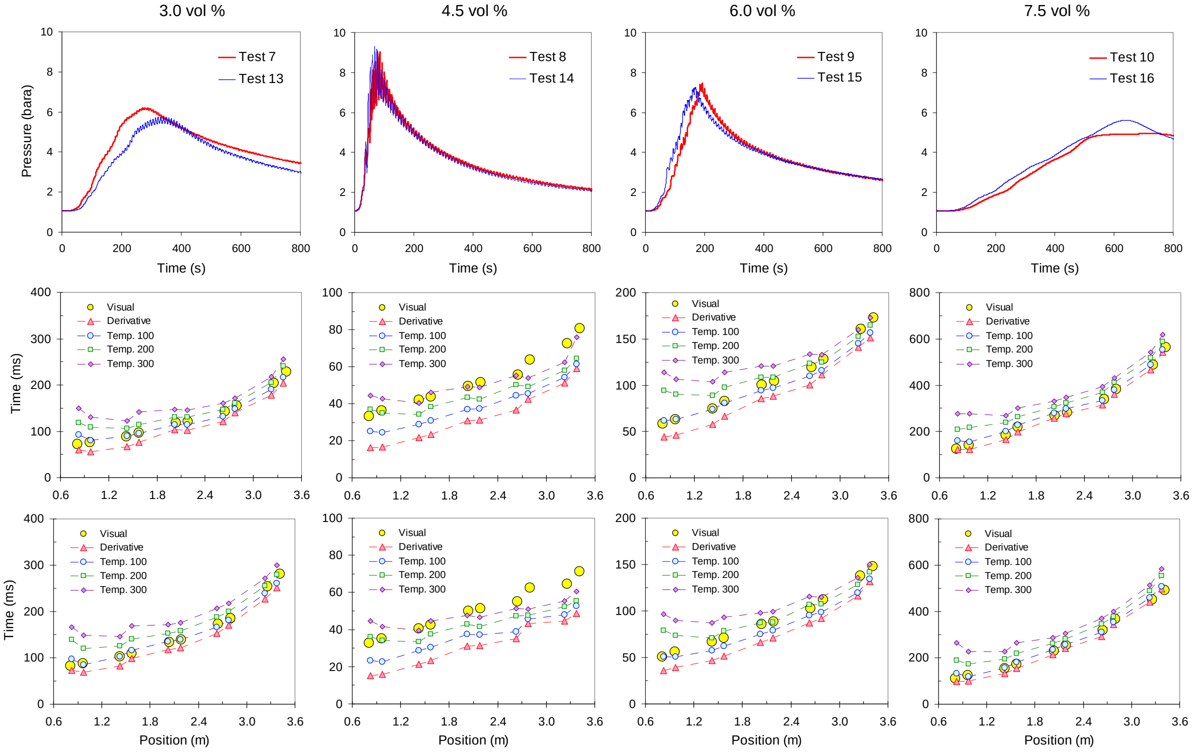

Figure 3. Measured pressure-time histories and estimated flame arrival times for two repeated tests in initially turbulent mixtures of 3.0, 4.5, 6.0 and 7.5 per cent propane in air.

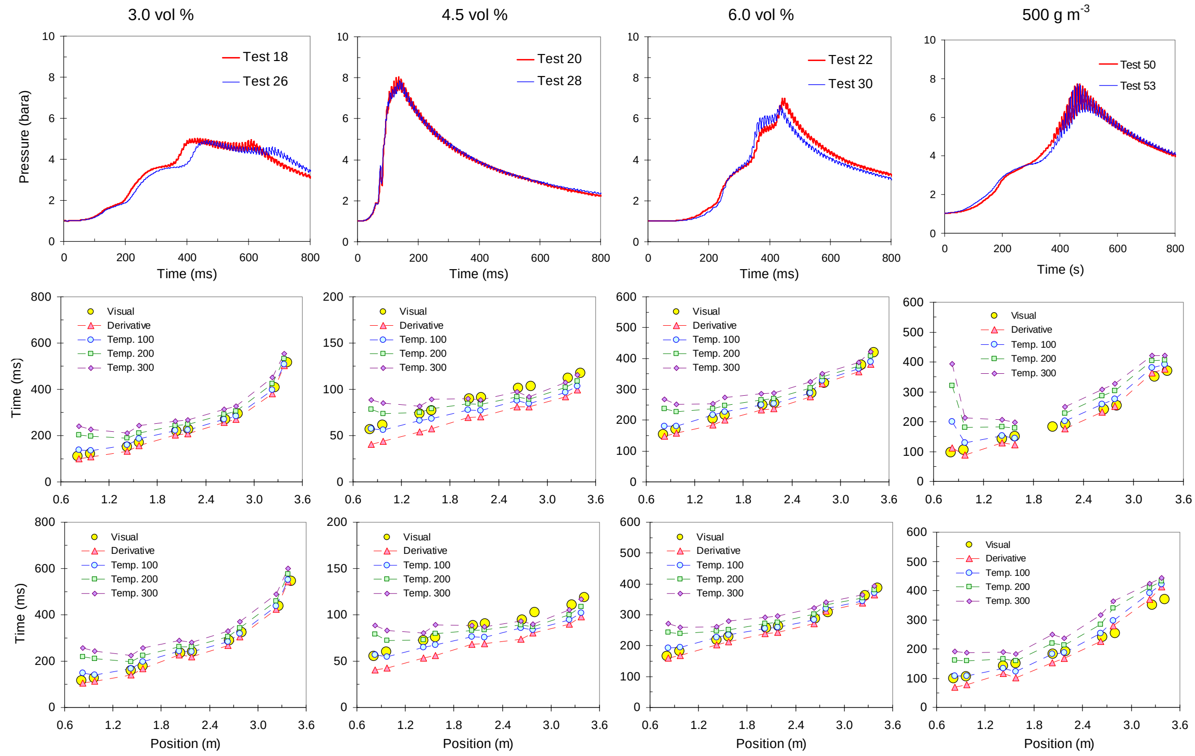

Figure 4. Measured pressure-time histories and estimated flame arrival times for two repeated tests with initially quiescent mixtures of 3.0, 4.5 and 6.0 per cent propane in air, as well as initially turbulent mixtures of 500 g m^{-3} maize starch in air.

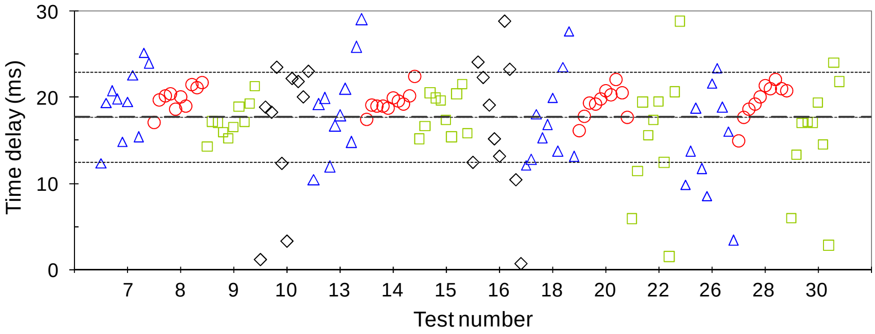

Figure 5. Delay between onset of rapid temperature rise, measured with thermocouples, and visual observation of flame arrival from high-speed video recordings of the experiments with gaseous fuel. The horizontal lines indicate the average value (17.7 ms), plus/minus one standard deviation (5.2 ms).

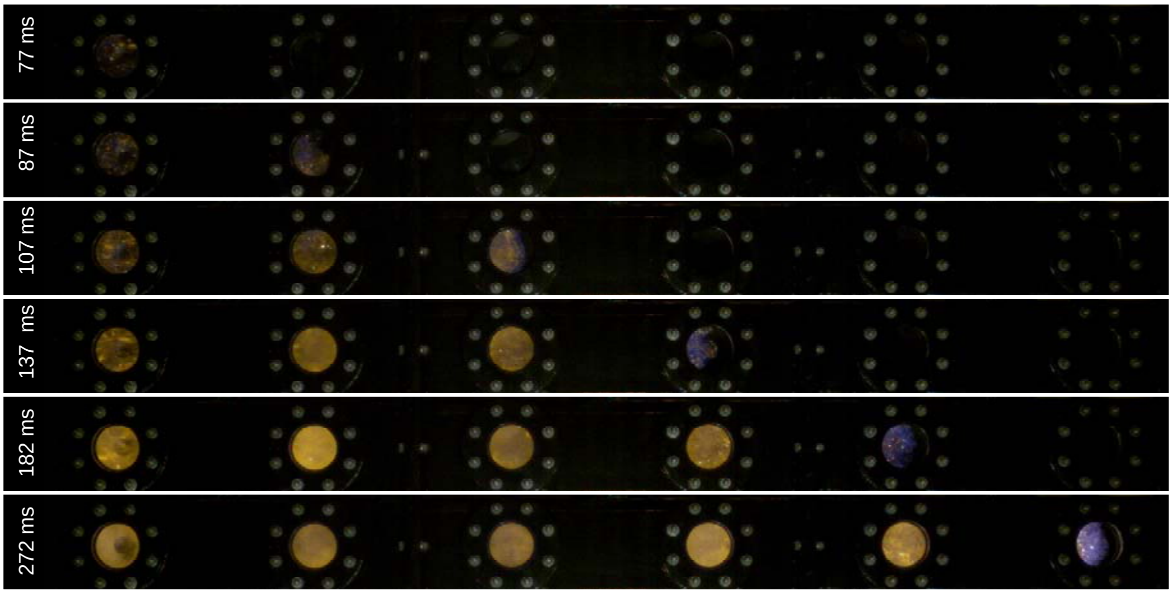

Figure 6. Selected frames from the high-speed video camera for Test 13: 3.0 % propane, initially turbulent.

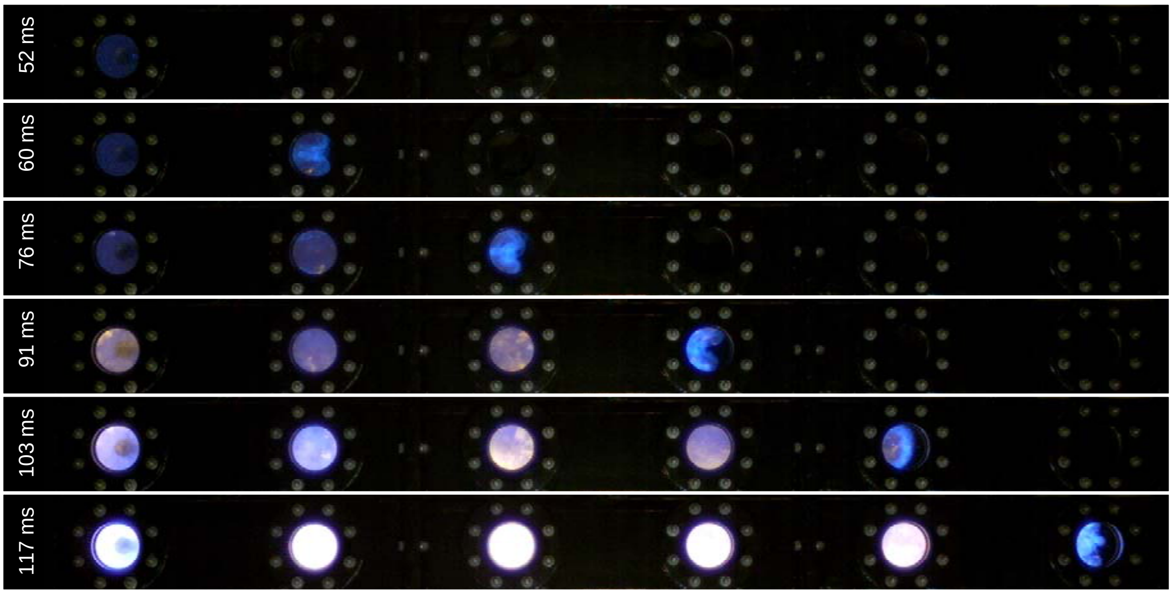

Figure 7. Selected frames from the high-speed video camera for Test 20: 4.5 % propane, initially quiescent.

Acknowledgements

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References

[1] Skjold, T. (2010). Flame propagation in dust clouds: challenges for model validation. Eighth ISHPMIE, Yokohama, Japan, 5-10 September 2010.

[2] Skjold, T. (2007). Review of the DESC project. Journal of Loss Prevention in the Process Industries, 20: 291-302.

[3] Skjold, T., Kalvatn, I.B., Enstad, G.E., & Eckhoff, R.K. (2009). Experimental investigation of the influence of obstacles on flame propagation in propane-air mixtures and dust-air suspensions in a 3.6 m flame acceleration tube. Poster at Twenty-second ICDERS, 27-31 July 2009, Minsk, Belarus.

[4] Skjold, T. (2010). Experimental investigation of turbulent flame propagation through propane-air and dust-air suspensions in a 3.6 metre flame acceleration tube. Poster at Thirty-third Symposium (Int.) on Combustion, 1-6 August 2010, Beijing, China.

[5] Enstad, G.A. (2009). Experimental investigation of the impedance measurement method for detecting dust and gas flames in a flame acceleration tube. MSc Thesis, University of Bergen.

[6] Kalvatn, I.B. (2009). Experimental investigation of the optical measurement method for detecting dust and gas flames in a flame acceleration tube. MSc Thesis, University of Bergen.

[7] Skjold, T. (2003). Selected aspects of turbulence and combustion in 20-litre explosion vessels. MSc Thesis, University of Bergen.

[8] Skjold, T. & Eckhoff, R.K. (2006). A balloon experiment for dust explosions. Work-in-progress poster at Thirty-first Symposium (Int.) on Combustion, 6-11 August 2006, Heidelberg: 606.

[9] Skjold, T., Eckhoff, R.K., Enstad, G.E., Kalvatn, I.B., van Wingerden, M. & van Wingerden, K. (2008). A modified balloon experiment for dust explosions. Work-in-progress poster at Thirty-second Symposium (Int.) on Combustion, 3-8 August 2008, Montreal, Canada.

[10] Pu, Y.K., Mazurkiewicz, J., Jarosinski, J. & Kauffman, C.W. (1988). Comparative study of the influence of obstacles on the propagation of dust and gas flames. Twenty-second Symposium (Int.) on Combustion: 1789-1797.

[11] Skjold, T., Pu, Y.K., Arntzen, B.J., Hansen, O.J., Storvik, I.E., Taraldset, O.J. & Eckhoff, R.K. (2005). Simulating the influence of obstacles on accelerating dust and gas flames. Poster, Twentieth ICDERS, July 31 - August 5, Montreal, Canada.

[12] Savitzky, A. & Golay, J.E. (1964). Analytical Chemistry, 36: 1627-1639.

[13] Skjold, T. & Castellanos, D. (2011). Influence of ignition energy and fuel concentration on turbulent flame propagation in propane-air mixtures and dust-air suspensions. Tenth IAFSS Symposium, University of Maryland, 19-24 June 2011.