

On Shock Reflections in Fast Flames

by

Logan Maley

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
For the M.A.Sc. degree in
Mechanical Engineering

Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
Faculty of Graduate and Post-doctoral Studies
University of Ottawa

© Logan Maley, Ottawa, Canada, 2015

Abstract

The present work investigates the structure of supersonic turbulent deflagration typically observed as precursors to the onset of detonation. These high-speed flames are obtained after detonation interaction with cylindrical obstacles. Two mixtures having the same propensity for local hot spot generation were used, namely stoichiometric hydrogen-oxygen and methane-oxygen. It was shown that the methane mixture sustained turbulent fast flames, while the hydrogen mixture did not. Three visualization techniques, Schlieren, shadowgraph, and direct chemi-luminescence were implemented to record the evolution of the structure following the detonation interaction with the obstacle. Detailed high-speed visualizations of the nearly two-dimensional flow fields permitted the identification of the key mechanism involved.

It was found that the shock reflections in methane permitted strong forward jets behind periodically formed Mach shocks on the front of the deflagration. These hot spots in the re-circulation zones of the jets provided local enhancement of the reactivity through mixing, supporting the formation of new generations of new hot spots.

The hot spot formation was identified as the prominent difference between the different mixtures. These reactive pockets further sustained the shock reflection processes. As the methane-oxygen fast flame propagates along the channel, the wave front was observed to organize into fewer modes and eventually led to a reflection capable of the transition to detonation.

In the hydrogen mixtures, at similar thermo-chemical parameters, self-sustained fast flames were not observed. Following detonation interaction in the hydrogen mixture, reactive reflections were observed. As the wave propagated downstream after a limited number of reactive reflections, the wave developed a planar wave front and decayed as the reaction zone trailed with an ever-increasing distance. It is postulated that the absence of the forward jets did not allow such fast flames to establish.

This jetting slip line instability in methane shock reflections was recently found to be correlated with the low value of the isentropic exponent and its control of Mach shock jetting described by Mach & Radulescu [1]. The lack of the forward jetting of the slip line in the hydrogen mixture with the higher value of the isentropic exponent is in agreement with the Mach & Radulescu.

Acknowledgements

For the years of guidance and friendship I would like to thank my supervisor Matei I. Radulescu. He has helped me to discover and hone my research skills over the five years we worked together. Quickly opening the door for me, he has provided many fantastic opportunities, immense guidance and trust throughout my studies.

I would also like to thank Shem Sabastien Lau-Chapdelaine for the computational assistance. As well, the support from Thanos Drivas, Jonathan Armstrong, and Nick Sirmas, along with all the members of the DRDL research group was appreciated. Experimental work conducted with Rohit Bhattacharjee was a great help with this work.

Family and friends have helped me through years of learning, always trying to help make sure I've been on the right path. My brother has always been there for support. My parents have been essential in helping me achieve my dreams. I would especially like to thank my mother for the hours of collaboration editing my writing. I would also like to thank my grandparents for showing me the meaning of hard work and perseverance. Lastly, I would especially like to thank Carmen Fletcher for her support while studying and while writing.

Contents

1	Introduction	1
1.1	Problem Definition	1
1.2	Background and Motivation	2
1.2.1	Review of Flame Acceleration	3
1.3	The Fast Flame	7
1.3.1	The Fast flames in Obstacle-Laden Channels	7
1.3.2	Shock Flame Interactions	7
1.3.3	The Fast Flames in Smooth Channels	9
1.4	The Current Study	14
2	Experimental Details	15
2.1	Physical Apparatus	15
2.2	Flow Visualization	15
2.2.1	The Schlieren System	15
2.2.2	The Edgerton Shadowgraph System	17
2.2.3	Self-luminous Experiments	17
2.3	Test Gases	19
2.4	Obstacle Configuration	20
2.5	Cell Size	21
3	Hydrogen Results	22
3.1	Single Obstacle Experiments	22
3.1.1	Schlieren Records	22
3.1.2	Shadowgraph Records	30
3.2	Five Obstacle Experiments	36
3.2.1	Shadowgraph Records	36

4	Methane Results	45
4.1	Single Obstacle Experiments	45
4.1.1	Schlieren Records	45
4.1.2	Shadowgraph Records	52
4.1.3	Self-Luminous Records	64
4.2	Five Obstacle Experiments	72
4.2.1	Schlieren Records	72
4.2.2	Shadowgraph Records	75
5	Discussion	92
5.1	Analysis	92
5.1.1	Chemical Kinetics	95
5.1.2	Hydrodynamics	97
5.1.3	Turbulence in the Forward Jet	99
5.1.4	Kolmogorov Scaling	100
6	Conclusion	102
6.1	Conclusions	102
6.2	Future work	103
A	Interpreting Experimental Images	110
A.1	Reading the Schlieren and Shadowgraph Images	110
A.2	Pre-compression in the tube	111
B	Image Adjustments	113
C	The High Voltage Igniter (HIV)	116
D	Image Velocimetry Uncertainty Calculations	126
E	Hydrogen-Oxygen Experiments	127
E.1	Five Cylinder Experiments	127
E.1.1	Shadowgraph Images	127
E.2	Single Cylinder Experiments	131
E.2.1	Shadowgraph Images	131
E.2.2	Schlieren Images	134

F	Methane-Oxygen Experiments	138
F.1	Five Cylinder Experiments	139
F.1.1	Schlieren Images	139
F.1.2	Shadowgraph Images	140
F.2	Single Cylinder Experiments	148
F.2.1	Schlieren Images	149
F.2.2	Shadowgraph Images	152
F.2.3	Self-Luminous Experiments	156
G	Full List of Experiments	170

List of Tables

2.1	Cell sizes and gap size ratios for the experimental gas mixtures at the maximum pressure $P_o = 20$ kPa	21
5.1	Thermo-chemical properties of the gas behind the Mach shocks in hydrogen-oxygen and methane-oxygen experiments 3.4 & 4.1, respectfully.	94
C.1	Specifications of the High Voltage Igniter (HVI)	118
G.1	A full list of experiments conducted for this study. Results of these experiments have been included as complimentary material.	171
G.2	A full list of experiments conducted for this study, continued	172
G.3	A full list of experiments conducted for this study, continued	173
G.4	A full list of experiments conducted for this study, continued. Experiments taken with Rohit Bhattacharjee	173
G.5	A full list of experiments conducted for this study, continued	174
G.6	A full list of experiments conducted for this study, continued	175
G.7	A full list of experiments conducted for this study, continued	176
G.8	A full list of experiments conducted for this study, continued	177
G.9	A full list of experiments conducted for this study, continued	178
G.10	A full list of experiments conducted for this study, continued	179

List of Figures

1.1	Sketch of the structure of the fast flame in a channel.	2
1.2	Experimental Schlieren images illustrating different stages of low-velocity flame acceleration adapted from Lee, images taken by Marksein	3
1.3	Fairweather's illustrations of flame acceleration depicting different time steps for comparison	4
1.4	Stroboscopic schlieren record of the onset of detonation in $H_2 + O_2$ at $P_o = 11.1\text{kPa}$	6
1.5	Series of schlieren images obtained from tests with 0.33 blockage ratio obstacles taken by Ciccarelli et. al.	8
1.6	Passage of a fast flame over a rough surface, taken by Ciccarelli et. al. . .	8
1.7	Schlieren images of two distorted flame bubbles traversed by the reflected shock wave taken by Thomas	10
1.8	(A) Streak self-luminous photograph of the Half CJ wave and streak self-luminous photograph of sudden transition to detonation taken by Chao .	11
1.9	Open shutter photograph of a failed detonation wave exiting a two-dimensional bank of cylinders taken by Radulescu	12
1.10	Images from separate experiments of the meta-stable combustion wave by Grondin & Lee	13
2.1	Sketch of the experimental apparatus, adapted from Thanos Drivas. . . .	16
2.2	The Z-type Schlieren set up as described by Settles	17
2.3	An Illustration depicting the shadowgraph system	18
2.4	Schematic of the experimental obstacles	20
3.1	Schlieren record of single cylinders experiment with reactive reflection $p_0 12.4\text{ kPa}$	24

3.2	Schlieren record of single cylinders experiment with reactive reflection $p_0 = 12.4$ kPa	25
3.3	Velocity record from the Schlieren images of hydrogen-oxygen $p_0 = 12.4$ kPa	26
3.4	Schlieren record of single cylinders experiment with reactive reflection $p_0 = 11.0$ kPa	27
3.5	Velocity record from the Schlieren images of hydrogen-oxygen $p_0 = 11.0$ kPa	28
3.6	Shadowgraph record of single cylinders experiment with unreactive reflection $p_0 = 10.3$ kPa	29
3.7	Velocity record from the Schlieren images of hydrogen-oxygen $p_0 = 10.3$ kPa	30
3.8	Shadowgraph record of hydrogen-oxygen detonation initiation upon reflection. $p_0 = 14.2$ kPa.	31
3.9	Shadowgraph record of hydrogen-oxygen detonation initiation upon reflection. $p_0 = 14.2$ kPa.	32
3.10	Velocity record from the shadowgraph images of hydrogen-oxygen $p_0 = 14.2$ kPa	33
3.11	Shadowgraph record of single cylinders experiment with reactive reflection $p_0 = 13.8$ kPa	34
3.12	Shadowgraph record of single cylinders experiment with reactive reflection $p_0 = 13.8$ kPa	35
3.13	Velocity record from the shadowgraph images of hydrogen-oxygen $p_0 = 13.8$ kPa	36
3.14	Shadowgraph images illustrating $2\text{H}_2\text{-O}_2$, $p_0 = 18.6$ kPa	38
3.15	Shadowgraph images illustrating $2\text{H}_2\text{-O}_2$, $p_0 = 18.6$ kPa	39
3.16	Velocity record from the shadowgraph images of hydrogen-oxygen $p_0 = 18.6$ kPa	40
3.17	Shadowgraph images illustrating $2\text{H}_2\text{-O}_2$, $p_0 = 17.2$ kPa	42
3.18	Shadowgraph images illustrating $2\text{H}_2\text{-O}_2$, $p_0 = 17.2$ kPa	43
3.19	Velocity record from the shadowgraph images of hydrogen-oxygen $p_0 = 17.2$ kPa	44
4.1	Schlieren record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 8.3$ kPa .	47
4.2	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 8.3$ kPa	48
4.3	Schlieren record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 3.4$ kPa .	49

4.4	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 3.4$ kPa	50
4.5	Schlieren record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 8.4$ kPa .	51
4.6	Velocity record from the schlieren images of methane-oxygen $p_0 = 8.4$ kPa	52
4.7	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, detonation initiation upon first reflection, $p_0 = 13.8$ kPa	53
4.8	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, detonation initiation upon first reflection, $p_0 = 13.8$ kPa	54
4.9	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 13.8$ kPa	55
4.10	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, detonation initiation upon second reflection, $p_0 = 11.0$ kPa	56
4.11	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, detonation initiation upon second reflection, $p_0 = 11.0$ kPa	57
4.12	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 11.0$ kPa	58
4.13	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 9.6$ kPa	59
4.14	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 9.6$ kPa	60
4.15	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 9.6$ kPa	61
4.16	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 8.5$ kPa	62
4.17	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 8.5$ kPa	63
4.18	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 8.5$ kPa	64
4.19	Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa	65
4.20	Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa	66
4.21	Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa	67
4.22	Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa	68
4.23	Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 6.9$ kPa	69

4.24	Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 6.9$ kPa	70
4.25	Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 6.9$ kPa	71
4.26	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 17.9$ kPa	73
4.27	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 17.9$ kPa	74
4.28	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 17.9$ kPa	75
4.29	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 9.6$ kPa	76
4.30	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 9.6$ kPa	77
4.31	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 9.6$ kPa	78
4.32	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 8.3$ kPa	79
4.33	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 8.3$ kPa	80
4.34	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 8.3$ kPa	81
4.35	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 7.6$ kPa Part 1	82
4.36	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 7.6$ kPa Part 2	83
4.37	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 7.6$ kPa Part 3	84
4.38	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 7.6$ kPa Part 4	85
4.39	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 7.6$ kPa Part 5	86
4.40	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 7.6$ kPa	87
4.41	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 6.9$ kPa	89
4.42	Shadowgraph images illustrating $\text{CH}_4 + 2\text{O}_2$ $p_0 = 6.9$ kPa	90
4.43	Velocity record from the shadowgraph images of methane-oxygen $p_0 = 6.9$ kPa	91
5.1	A comparison of reflection behaviour between hydrogen-oxygen and methane-oxygen	92
5.2	Example of methane-oxygen ignition delay calculations depicting the parameters t_{ig} and t_{reac}	95
5.3	Inert shock reflection pattern in $2\text{H}_2\text{-O}_2, p_0 = 10.3$ kPa.	97
5.4	Inert shock reflection pattern in $\text{CH}_4 + 2\text{O}_2; p_0 = 3.44$ kPa.	98

5.5	Inert shock reflections in modelled Hydrogen-Oxygen and Methane-Oxygen mixtures; the incident shock Mach number is taken as 1/2 of the CJ velocity for both cases, 30° incidence angle and $\gamma = 1.36$ and 1.2 respectively.	99
A.1	Simultaneous schlieren and OH* image by J. Austin at Caltech, Shot 157: 2H ₂ -O ₂ -3.5N ₂ $P_0 = 21$ kPa	111
B.1	Comparison of basic tone adjustments	114
B.2	Comparison of the adjustments and background subtraction	115
C.1	Image of the High Voltage Igniter (HVI), courtesy of S. Kamenskih	116
C.2	Circuit diagram of the High Voltage Igniter (HVI)	117
C.3	Waveform, current and voltage, results tested under $V_0 = 20$ kV	119
C.4	Waveform, current and voltage, results tested under $V_0 = 25$ kV	119
E.1	Full record of shadowgraph images illustrating 2H ₂ -O ₂ , $p_0 = 18.6$ kPa - Part A	127
E.2	Full record of shadowgraph images illustrating 2H ₂ -O ₂ , $p_0 = 18.6$ kPa - Part B	128
E.3	Full record of shadowgraph images illustrating 2H ₂ -O ₂ , $p_0 = 17.2$ kPa - Part A	129
E.4	Full record of shadowgraph images illustrating 2H ₂ -O ₂ , $p_0 = 17.2$ kPa - Part B	130
E.5	Full record of shadowgraph record of hydrogen-oxygen detonation initiation upon reflection. $p_0 = 14.2$ kPa.	131
E.6	Full record of shadowgraph record of single cylinders experiment with reactive reflection $p_0 = 13.8$ kPa	132
E.7	Shadowgraph record of hydrogen-oxygen, $p_0 = 8.6$ kPa, detonation failure around the single cylinder and subsequent wave decay	133
E.8	Schlieren record of single cylinders experiment with reactive reflection $p_0 = 12.4$ kPa	134
E.9	Schlieren record of single cylinders experiment with reactive reflection $p_0 = 12.4$ kPa	135
E.10	Shadowgraph record of single cylinders experiment with reactive reflection $p_0 = 11.0$ kPa	136
E.11	Complete shadowgraph record of single cylinders experiment with unreactive reflection $p_0 = 10.3$ kPa	137

F.1	Full Record of Schlieren images illustrating CH_4+2O_2 $p_0 = 17.9$ kPa . . .	139
F.2	Full record of Shadowgraph images illustrating CH_4+2O_2 $p_0 = 6.9$ kPa - Part A	140
F.3	Full record of Shadowgraph images illustrating CH_4+2O_2 $p_0 = 6.9$ kPa - Part B	141
F.4	Frames of the shadowgraph image illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa, 25.63 microseconds, 4.84 microsecond exposure, 39016.7 fps	142
F.5	Frames of the shadowgraph image illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa, 25.63 microseconds, 4.84 microsecond exposure, 39016.7 fps	143
F.6	Full record of Shadowgraph images illustrating CH_4+2O_2 $p_0 = 8.3$ kPa .	144
F.7	Full record of Shadowgraph images illustrating CH_4+2O_2 $p_0 = 8.3$ kPa .	145
F.8	Full record of shadowgraph images illustrating CH_4+2O_2 $p_0 = 9.6$ kPa . .	146
F.9	Full record of shadowgraph images illustrating CH_4+2O_2 $p_0 = 9.6$ kPa . .	147
F.10	Full Schlieren record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 8.3$ kPa	149
F.11	Schlieren record of methane-oxygen inert shock shock reflection 3.5 kPa .	150
F.12	Full Schlieren record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 3.4$ kPa	151
F.13	Full experimental of record shadowgraph record of single cylinder exper- iment $\text{CH}_4 + 2\text{O}_2$, detonation initiation upon first reflection, $p_0 = 13.8$ kPa	152
F.14	Shadowgraph record of single cylinder experiment $\text{CH}_4 + 2\text{O}_2$, detonation initiation upon second reflection, $p_0 = 11.0$ kPa	153
F.15	Full experimental record of shadowgraph record of single cylinder experi- ment $\text{CH}_4 + 2\text{O}_2$, $p_0 = 9.6$ kPa	154
F.16	Full Experimental shadowgraph record of single cylinder experiment CH_4+ 2O_2 , $p_0 = 8.5$ kPa	155
F.17	Part 1 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa	157
F.18	Part 2 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa	158
F.19	Part 3 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa	159
F.20	Part 3 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa	160
F.21	Part 1 of Direct visualization record of the self luminosity in methane- oxygen at $p_0 = 6.9$ kPa	161

F.22	Part 2 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa	162
F.23	Part 3 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa	163
F.24	Part 4 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa	164
F.25	Part 1 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa	165
F.26	Part 2 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa	166
F.27	Part 3 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa	167
F.28	Part 4 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa	168

Chapter 1

Introduction

1.1 Problem Definition

Flame acceleration in reactive gas mixtures poses serious concerns in many areas. One common area of interest is accidental industrial or residential gas leaks. In an environment where a reactive gas and an ignition source are present, the type of possible combustion is of great concern. This work seeks to augment the understanding of flame acceleration, focusing on supersonic deflagration waves, the fast flames, and the transition to detonation in order to gain a predictive capability.

The fast flame is a quasi-steady combustion wave travelling at speeds which lie between classical detonation, the Chapman-Jouguet (CJ) velocity, and deflagration velocities. The fast flame is similar in basic structure to the detonation, as seen in Figure 1.1. Composed of a shock wave supported by a trailing reaction zone, yet it travels at approximately half the ideal CJ detonation velocity. The fast flame has been seen to display a very turbulent structure coupled with significant transverse pressure oscillations, as will be discussed in detail.

Current theories are unable to predict the extent of flame acceleration or explain the final high-velocity stage of the deflagration to detonation transition (DDT) process, known as the fast flame. This study will attempt to clarify the underlying properties and mechanisms responsible for the fast flame propagation. Using state of the art visualization techniques, coupled with theoretical calculations, this study examines the structure of the fast flame to determine the controlling mechanism which is responsible for the behaviour of the fast flame as a phenomenon.

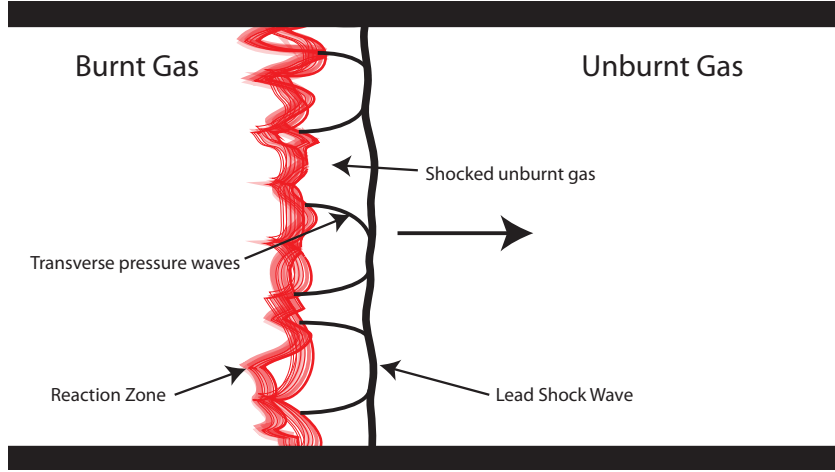


Figure 1.1: Sketch of the structure of the fast flame in a channel.

1.2 Background and Motivation

Reactive gases, typically fuel/oxidizer mixtures, have two very different combustion regimes, the detonation and the deflagration. A deflagration wave is a diffusion controlled flame, with typical burning velocities of a few metres per second and low-pressure changes. A detonation is a supersonic reactive compression wave dominated by auto-ignition, where a shock wave is in-phase with the closely coupled reaction zone through the chemical induction delay, typical burning velocities of two- to three-thousand meters per second with twenty- to thirty-times pressure increase across the wave. Partly due to the very high-speeds and large pressure jumps across the detonation wave, there is a lack of predictive understanding about these waves and their origin [2][3].

A detonation can be directly initiated by a large energy deposition or can undergo a process known as deflagration to detonation transition (DDT). The mechanisms controlling DDT are largely understood qualitatively especially at the low speed stages [4][5]. The high-speed regimes and quantitative aspects of the DDT process remain to be fully understood. The final high-speed stage of the DDT process, known as the fast flame, is a meta-stable regime which consists of a shock wave supported by a reaction zone. This has been observed to persist for many tube diameters yet the propagation mechanism remains a topic of debate [6]. During flame acceleration this regime is terminated by the onset of a detonation. Several mechanisms have been identified that enable the final transition to take place [7]. The understanding of the fast flame stage remains to be clarified.

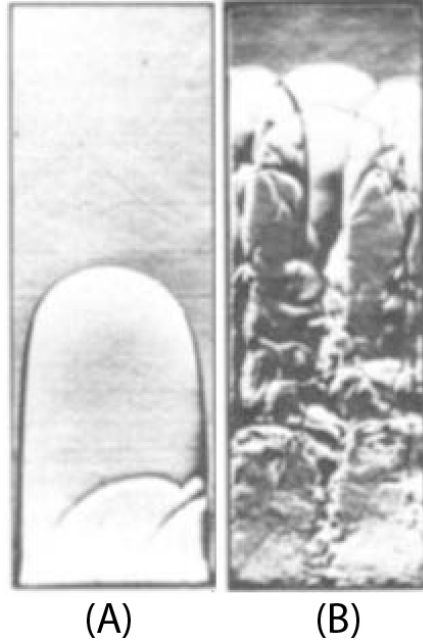


Figure 1.2: Experimental Schlieren images illustrating different stages of low-velocity flame acceleration adapted from Lee [12], images taken by Marksein [13]

1.2.1 Review of Flame Acceleration

The early, low-velocity stages of the transition process have been the subject of a substantial amount of investigation to clarify the physical mechanisms responsible for the flame acceleration. It has been observed that flame acceleration is heavily dependant on geometry and boundary conditions [8]. For simplicity, we will illustrate flame acceleration in a smooth channel.

When a flame is ignited at the closed end of a tube the hot products expand, sending out pressure waves. These pressure waves begin to perturb the flow ahead of the flame. Velocity gradients begin to form causing the center of the flame to accelerate. This results in a flame similar to that in frame (A) of Figure 1.2. These gradients begin to stretch and fold the flame, similar to that seen in frame (B) of Figure 1.2. As the flame stretches and folds, the surface area increases and the burning rate increases [9]. As the burning rate increases, the production of expanded burnt products increases, sending more pressure waves forward which in turn creates larger velocity gradients. This creates a positive feedback loop between the increasing burning rate and the flame stretching [4][3][10][11].

The flame acceleration process has been observed to be enhanced in rough-walled or

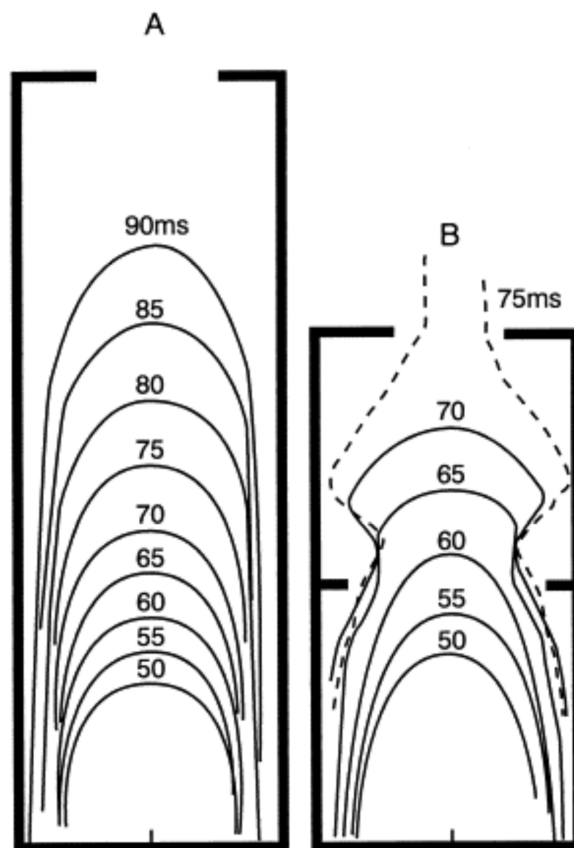


Figure 1.3: Fairweather's illustrations of flame acceleration depicting different time steps for comparison in (A) smooth tube, (B) obstacle-laden tube [11]

obstacle-filled channels, as shown in Figure 1.3. It has been postulated that the roughness introduces intense turbulence to the flame [14] through flame folding and pressure wave generation which enhances the burning rate [15]. The increased flame velocity induced by the roughness is illustrated by the time steps in frame (B) of Figure 1.3 compared to the time steps in frame (A) for the smooth channel. Pressure wave generation has been seen to enhance burning rates in gases with higher chemical sensitivities, usually gases which display irregular detonation patterns [16]. Researchers such as Schelkin, Teodorczyk and Ciccarelli have observed that placing a periodic obstacle, such as a long spiral wire or sand [17][18][16], along the walls of the channel can greatly reduce the length required for DDT to occur [15][19].

The pressure waves sent ahead of the flame are able to eventually coalesce into a shock wave. The flame continues to strengthen the shock wave, and the shock wave further

pre-conditions the un-burnt gas by increasing the un-burnt pressure and temperature. This pre-conditioning results in a higher burning rate, which in turn gives rise to larger velocity gradients, causing more flame folding and stretching. As the stretching and folding of the flame increases, the flame consumes more gas per unit projected area thus increasing the burning rate. This generates a positive feedback loop. As the velocity gradients increase, the Reynolds number of the flow can reach a critical value and can lead to transition to a turbulent flame [4]. The turbulent pre-conditioned state of the un-burnt gas rapidly increases the burning rate, accelerating the flame. The turbulent flame accelerating in the pre-conditioned gas continues to emit acoustic pressure waves forward into the un-burnt gas. These waves further strengthen the lead shock wave [20]. As these pressure waves pass ahead of the reaction zone they pre-condition the state and can cause local gradients in the induction delay at the small scales. These gradients can locally amplify the pressure waves through the *Shock Wave Amplification due to Coherent Energy Release* or SWACER mechanism [21].

Eventually the combustion wave then reaches the fast flame stage. The fast flame is very poorly understood and is generally short-lived. When the appropriate conditions are present the flame will reach a critical point where transition to detonation will occur. Figure 1.4 shows these later stages of the DDT process beginning with the turbulent flame brush coupled shock wave where a detonation is initiated from the flame brush, overtaking the lead shock wave.

Several different pathways of transition from the fast flame to detonation have been identified in the past [2]; for example, precursor shock initiation, hot spot initiation, compression initiation from the turbulent flame brush and progressive transverse wave amplification. The final transition has been observed to depend on the pattern of the shock fronts which developed during the turbulent flame acceleration phase [7]. Regardless of the exact mode of transition, it is common for the transition to take place through one of two distinct mechanisms, shock initiation or SWACER. Shock initiation occurs when a strong shock reflection is able to directly initiate an overdrive detonation at a discrete location. Conversely, the SWACER mechanism occurs if local gradients of ignition delay can synchronize with the passage of a shock wave. This acceleration can form a local detonation [21]. Regardless of the mechanism, the detonation then expands and engulfs the entire flame front developing into a self-sustained detonation.

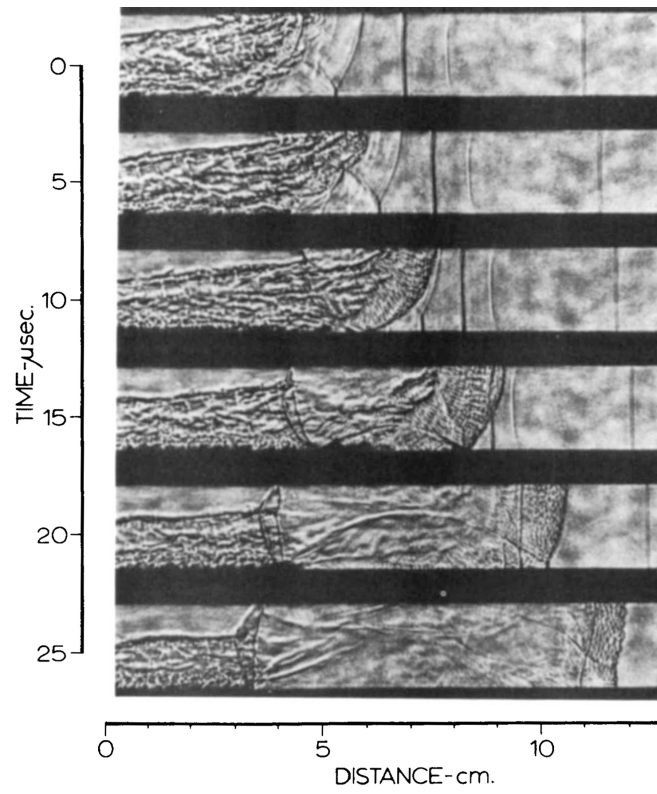


Figure 1.4: Stroboscopic schlieren record of the onset of detonation in $H_2 + O_2$ at $P_o = 11.1\text{kPa}$, with the localized auto-explosion originating in the vicinity of the turbulent flame brush taken by Oppenheim [7]

1.3 The Fast Flame

In order to complete the understanding of the DDT process, researchers have recently turned their attention to the fast flame. Attempts have been made to isolate this stage of the DDT process in order to better understand the phenomenon. Different paths have been taken to isolate the fast flame and they will be discussed here.

1.3.1 The Fast flames in Obstacle-Laden Channels

Ciccarelli and colleagues have observed that as a combustion wave accelerates in an obstacle-laden channel the velocity approaches the speed of sound of the products. In some cases the flame is choked and the velocity does not increase further. Some gas mixtures have been observed to display an increase in velocity to half the CJ velocity. Experiments conducted in channels with periodic obstacles have been shown to sustain these high-velocity shock flame complexes for longer distances. Figure 1.5 taken from Ciccarelli et. al. illustrates a good example of these waves. The obstacles are thought to promote shock-flame interactions leading to higher flame velocities than possible in a smooth channel [22].

Ciccarelli et. al. recently clearly showed this increased velocity of the combustion waves in the presence of rough boundary conditions [16]. They observed that a globally quasi-steady combustion wave, described in the past as a fast flame, travelling at speeds between the speed of sound in the products and the ideal Chapman-Jouguet velocity, was able to develop in the presence of the rough walls. The roughness is thought to be able to promote turbulence and transverse pressure wave activity similar to Figure 1.6. Ciccarelli also linked the increased transverse wave activity to this development of the fast flame.

Researchers have also conducted experiments in rough walled channels with porosity [16]. The addition of porosity effectively damped the transverse wave action, similar to experiments done with irregular detonations [23]. With the lack of transverse wave action, the fast flames showed a significantly lower maximum velocity, agreeing that flame acceleration is significantly enhanced by transverse pressure waves.

1.3.2 Shock Flame Interactions

In order to study the fast flame without relying on the low-velocity stages of the flame acceleration, Thomas examined the interaction between laminar flame bubbles and shock

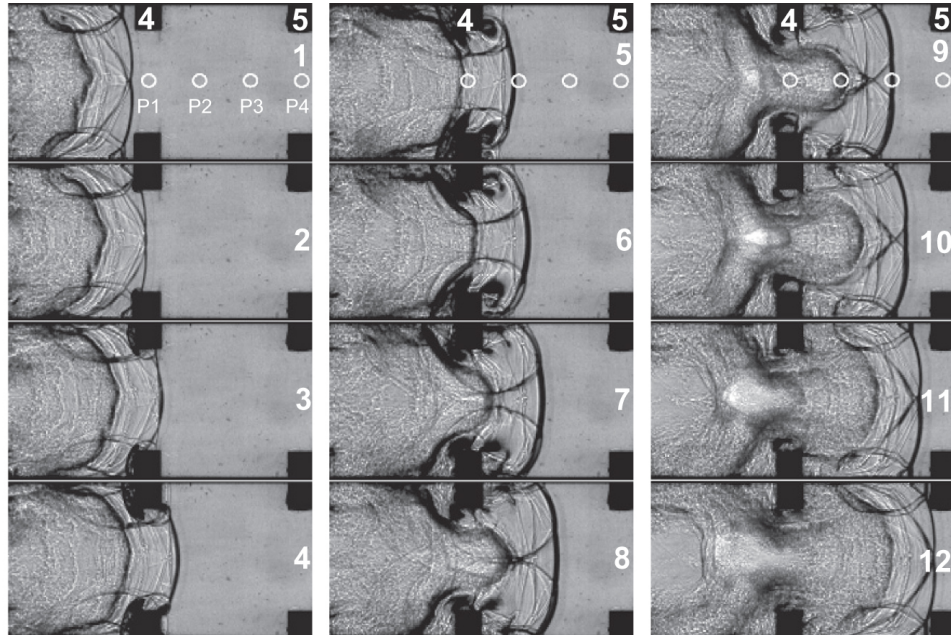


Figure 1.5: Series of schlieren images obtained from tests with 0.33 blockage ratio obstacles. Inter-frame time is $33 \mu s$. Taken by Ciccarelli et. al. [22]

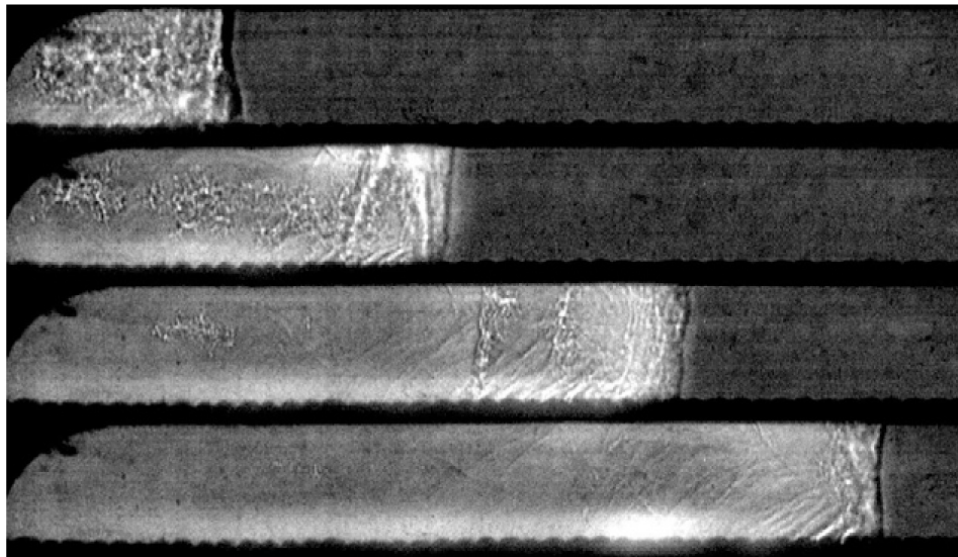


Figure 1.6: Passage of a fast flame over a rough surface along the bottom wall. Transverse waves can be seen clearly reflecting off the roughness. Taken by Ciccarelli et. al. [16]

waves [24]. Thomas noted that these waves seemed to rely on diffusion and turbulence and observed strong pressure oscillation accompanying the waves. However, he observed that these waves do not fit the description of a detonation as the fast flames travel quasi-steadily at half the Chapman-Jouguet (CJ) velocity. He described them as a “Strange wave.”

1.3.3 The Fast Flames in Smooth Channels

Other researchers have conducted experiments on detonation interaction with obstacles to quench the detonation which can form the half-CJ waves, the fast flame. Detonation interaction with different obstacles has been studied for many purposes in the past, originally to study detonation behaviour and limits.

When the detonation wave interacts with the obstacles blocking its path, the lead shock is reflected and transmitted with the decoupled reaction zone around the obstacle. Different types of obstacles have been tested in the past, some examples including: steps [25], converging-diverging ramps [26][27], porous plates [28][29][6], porous mediums [14][30], cylinders [31][32], and sudden area changes [33][34]. Regardless of the specific shape of the obstacle, the global behaviour remains the same; detonation attenuation leading to detonation failure and decoupling of the shock and reaction zone. The goal of many of these studies was to examine detonation limits and detonation re-initiation behaviour. However, increased attention has been paid to the fast flames produced by these experiments in recent years.

Chao, in her PhD work, conducted experiments using detonation interaction with a porous plate [29]. Using streak self-luminous and streak Schlieren imaging, she was able to examine the behaviours of the waves resulting from the detonation-plate interaction. If the mixture was sensitive enough, the detonation would drive strong shock waves through the plates and the detonation would continue to propagate. At lower pressures, i.e. a less sensitive mixture, the detonation would fail when passing through the plate. The resulting wave would travel at half CJ velocity, seen in Figure 1.8 (A). She observed that in unstable mixtures these waves would continue many tube diameters at a constant velocity before detonation initiation. Under certain conditions it was found that the half CJ wave would suddenly transition to a detonation as seen in Figure 1.8 (B). It was concluded that the transverse pressure fluctuations were vital in maintaining the fast flames, potentially through an increased turbulence but this remained unclear. Her work was in good agreement with Thomas’ observation of strong pressure in the reaction zone.

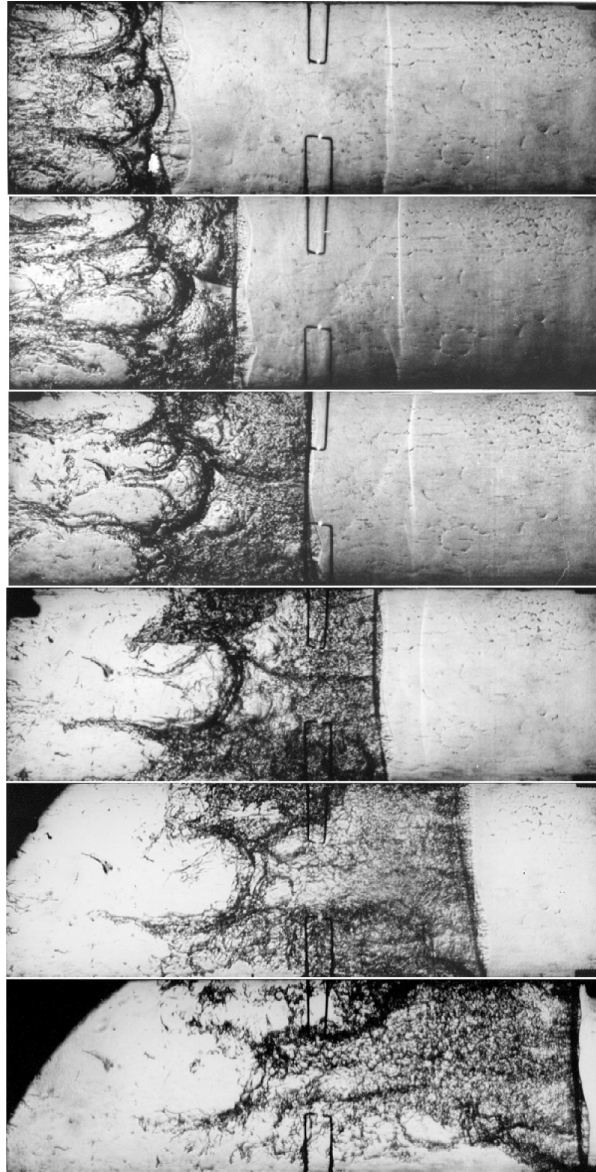


Figure 1.7: Schlieren images of two distorted flame bubbles as they are traversed by the reflected shock wave producing what is described as a “strange wave.” Mixture $\text{C}_2\text{H}_4 + 3\text{O}_2 + 4\text{N}_2$. Incident shock Mach number 1.7, frame interval $50\ \mu\text{s}$.

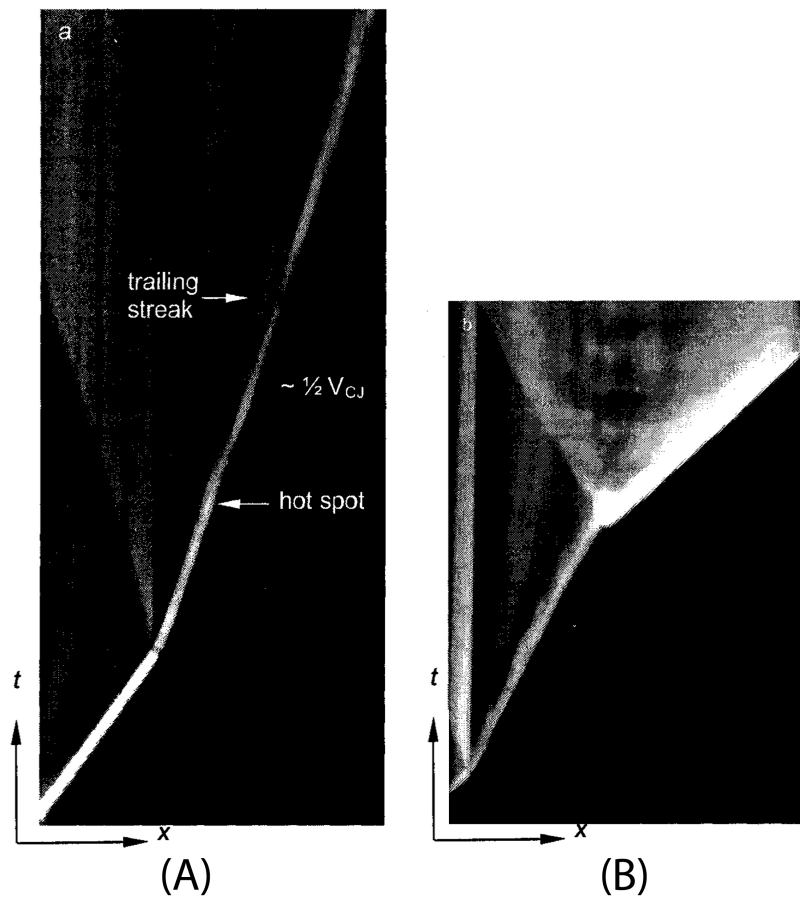


Figure 1.8: (A) Streak self-luminous photograph of the Half CJ wave and streak self-luminous photograph of sudden transition to detonation. Both taken by Chao [29]

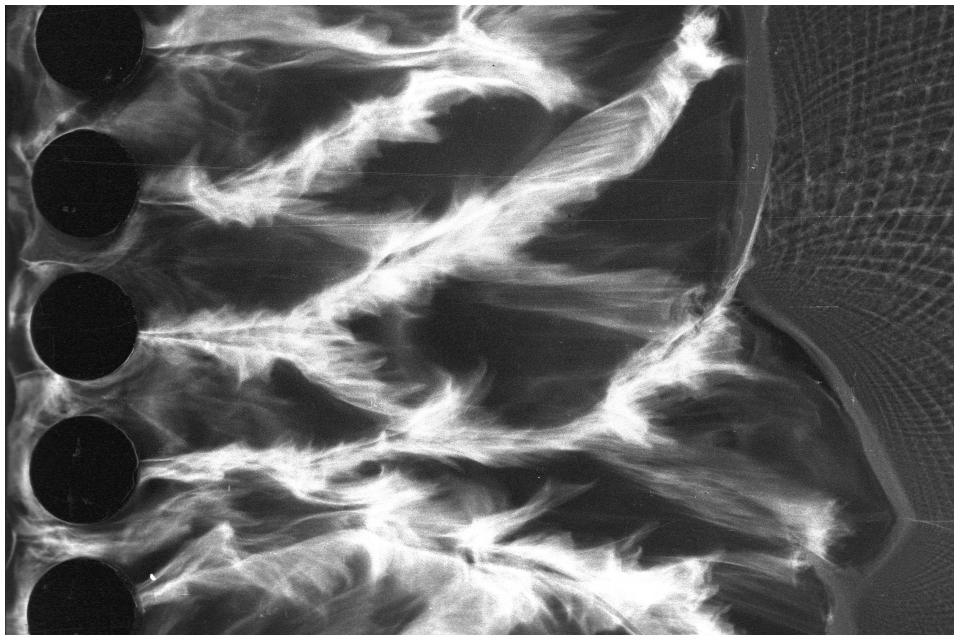


Figure 1.9: Open shutter photograph of a failed detonation wave exiting a two-dimensional bank of cylinders taken by Radulescu [30]

Radulescu and Maxwell [30] investigated the re-initiation of a detonation wave at the exit of a two-dimensional array of staggered cylinders, Figure 1.9. The experimental open-shutter photographs taken by Radulescu suggested that intense turbulent mixing along shear layers is present following hot spot ignition points and associated transverse pressure wave activity. Their numerical study suggested that such high deflagration speeds required auto-ignition spots via shock compression to drive such strong transverse pressure wave activity before sudden transition to detonation occurred. These observations point towards the presence of both diffusive and non-diffusive mechanisms playing significant roles in this acceleration process. The study also postulated that the fast flame propagation was controlled by a similar mechanism to the propagation of unstable detonation waves.

To better understand the structure of these fast flames specifically, Lee and Grondin implemented schlieren photography and conducted experiments in a thin channel examining detonation interaction with a porous plate and the resulting fast flame [6]. They observed a structure of a fast flame in the irregular gas, propane-oxygen, as far as three channel heights downstream, seen in Figure 1.10, noting it as a turbulent meta-stable wave before eventual transition to detonation. As noted Chao, they did not observe

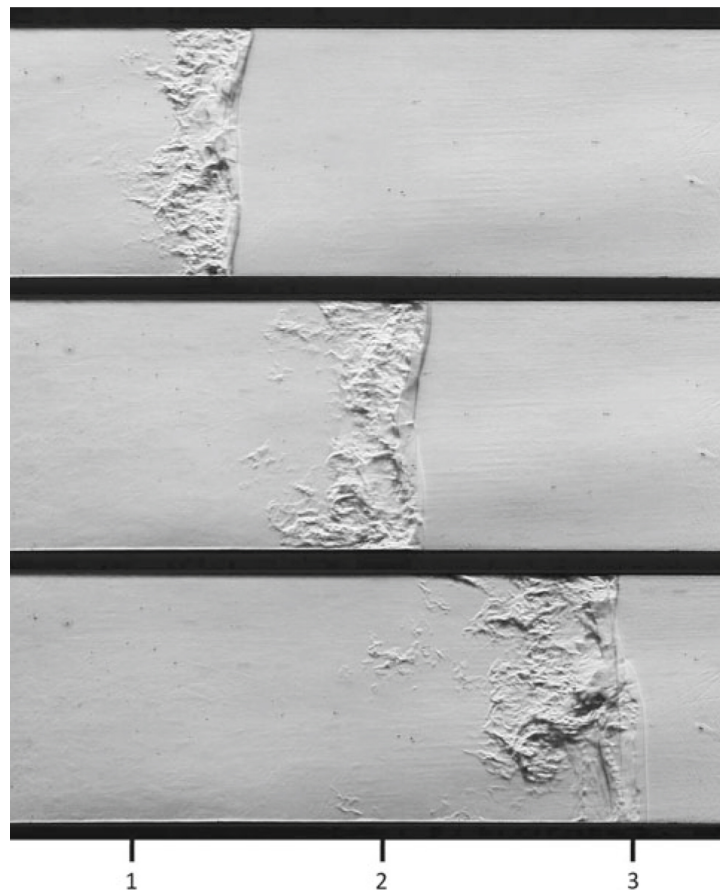


Figure 1.10: Images from separate experiments of the meta-stable $\text{C}_3\text{H}_8+5\text{O}_2$ combustion wave at $p_o = 4$ kPa by Grondin & Lee [6]

the fast flame when testing a gas mixture which exhibits classically regular structured detonations, in this case, acetylene oxygen diluted in 70 percent argon.

Previous works by Bhattacharjee focused on detonation interaction with a single cylindrical obstacle to examine the direct ignition of the Mach stem [32][31]. This study identified conditions for which detonation initiation would take place immediately, hot spots would form, as well as conditions for which shock decay would dominate in the near field. It was observed that hot spot ignition in the near field was accompanied by the appearance of a strong forward jet behind the Mach stem after a shock reflection. Also, observations of reactive transverse waves were made following strong transitional Mach reflections.

1.4 The Current Study

In order to clarify the underlying mechanism responsible for the fast flame behaviour, it is important to clearly observe the structure of the fast flame in a time resolved manner. To accomplish clear observations, optical access of the entire channel height is used to allow Schlieren and shadowgraph visualization techniques. The fast flames were produced through detonation failure in the wake of a cylindrical obstacle. This allows for a high level of reproducibility and ensures the fast flame originates from well established initial conditions. Using scaled obstacles, the phenomenon was examined in the near and far fields in an attempt to be independent of the obstacles' geometry and permit the construction of the evolution of the flow field.

To identify the controlling parameters and underlying mechanisms responsible for the propagation of the fast flame, this study tested two gas mixtures, stoichiometric hydrogen-oxygen and methane-oxygen. These gases have different properties, thus the different behaviours displayed by these two gases will provide insight into the parameters and mechanisms which control the fast flame propagation.

Chapter 2

Experimental Details

2.1 Physical Apparatus

The experiments performed for this work were conducted in a thin rectangular channel 3.5 m long divided into 3 sections of equal length, 203.2 mm high and 19.1 mm wide. To allow optical access, the final section was equipped with glass windows divided into two sections allowing a visual access of 482.6 mm by 203.2 mm each, shown in Figure 2.1. Standard non-tempered glass 19 mm thick was used. Along the top and bottom of the channel, 60 equally spaced access ports were used to fit sensors or plumbing.

The high aspect ratio of the channel allows for quasi-two dimensional shock dynamics and minimizes the visual integration across the width. This channel size, in conjunction with the pressures at which the experiments were performed, forced the shock dynamics of the fast flame structure to become essentially two dimensional.

2.2 Flow Visualization

2.2.1 The Schlieren System

Two different flow visualization techniques were used. A high resolution Z-type Schlieren system [35] with a 317.5 mm field of view permitted us to probe small scales, depicted in Figure 2.2. First surface parabolic mirrors, 1.905 m focal length, $f/6$ aperture, with a surface precision of $1/8$ the wavelength of light (632 nm) were used.

Figure 2.2 shows a schematic of the Schlieren system, similar to that of Settles [35]. An arc lamp, used as a light source, was strong enough to overpower the self-luminosity

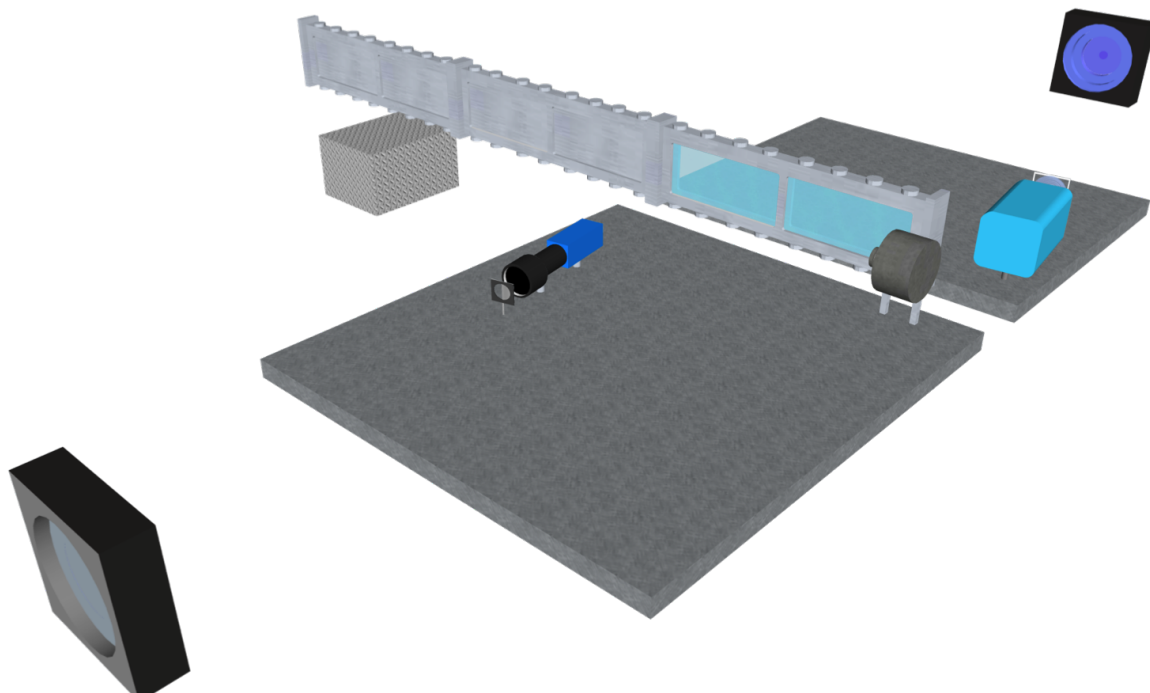


Figure 2.1: Sketch of the experimental apparatus, adapted from Thanos Drivas.

of the detonation in the Schlieren system. A 120 mm glass lens was used to focus the light to a small point, $\sim 3\text{-}5$ mm diameter, at the focal point of the parabolic mirrors. The light was then expanded to a diameter of ~ 50 cm with the first mirror in the center to ensure complete and even coverage of the mirror. The light was parallelized by the first parabolic mirror. The column of light then travelled across the room, through the optical section of the shock tube, before impinging upon the second Schlieren mirror. The second Schlieren mirror then condensed the light back to the small point. A knife edge was used to cut off half of the point. The remaining half expanded into the 80 mm lens, focused to infinity, attached to the high-speed camera.

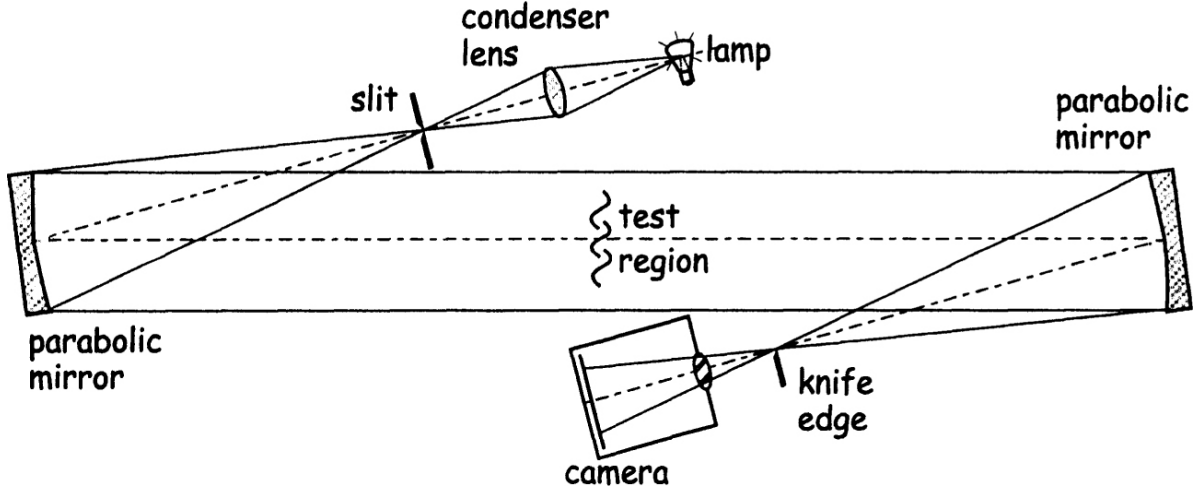


Figure 2.2: The Z-type Schlieren set up as described by Settles [35]

2.2.2 The Edgerton Shadowgraph System

The second optical system used was a large-scale Edgerton shadowgraph system [36]. This was implemented using a 2 m by 2 m retro-reflective screen, allowing visual access to the experiments over the entire 1 m viewing section, depicted in Figure 2.3. The details of this system have recently been published [37]. The shadowgraph system was used by placing the shock tube at $\sim d/f = 1/2$ to attain the clearest images. The collimated light exiting from the arc lamp was condensed to a 3-5 mm point using a 50 mm glass lens. This point was focused onto a 10 mm diameter cylindrical rod mirror cut at a 45° angle which was glued to a clear lens filter mounted to a rotating lens holder, allowing easy alignment. This projected the light onto the retro-reflective screen as if it directly emanated from the camera lens, increasing luminosity of the returned image to the camera.

Both systems used the same light source and camera to permit the Schlieren and shadowgraph images. A 1600 W continuous xenon arc lamp, made by Newport, and a high-speed video camera, Phantom v1210 made by Vision Research, recorded high-speed videos at a maximum useful speed of approximately 86 058.5 fps at a reduced resolution, using 348 x 256 pixels, and a $0.91\mu\text{s}$ exposure.

2.2.3 Self-luminous Experiments

Experiments were conducted and observed directly with the high-speed camera to observe the chemi-luminescence. This provides a new perspective of the same phenomenon

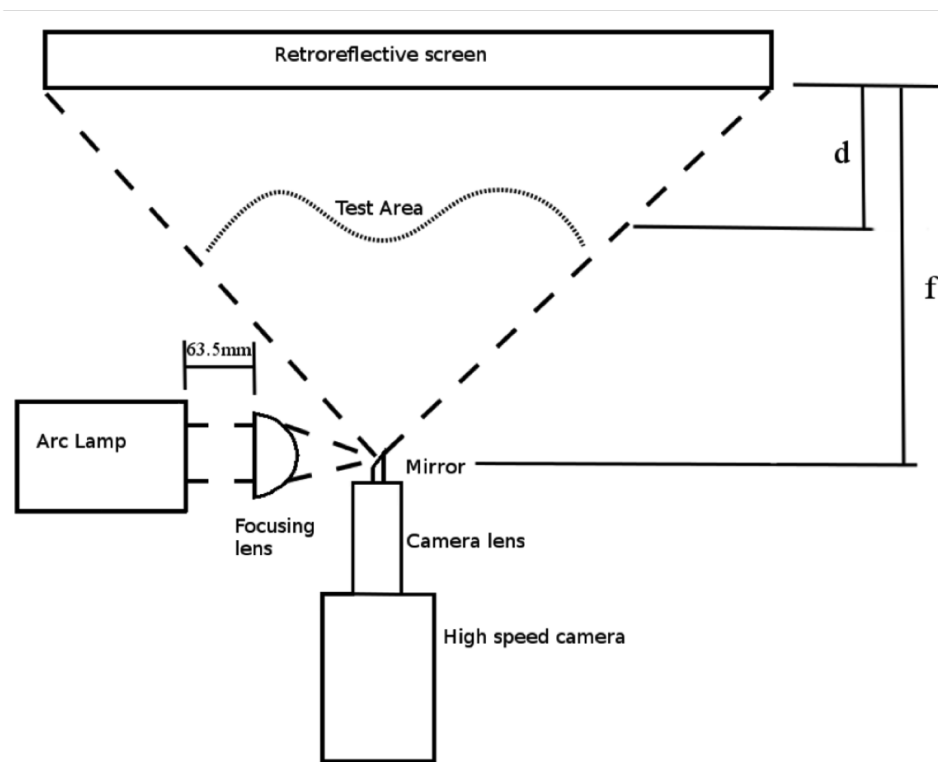


Figure 2.3: An Illustration depicting the shadowgraph system, adapted from [37]

compared with the Schlieren and shadowgraph methods used above which visualize the density gradients. Chemi-luminescence provides a direct view of the hot spots and their behaviour.

Chemi-luminescent photographs were successfully captured using the methane mixture, however, the hydrogen mixture was unable to be visualized. The light spectrum of the hydrogen-oxygen combustion was not able to be captured by the high-speed camera. The chemi-luminescent photographs in this work do not discriminate between specific wavelengths of light. The wide spectrum which is observed by the Phantom v1210 was captured. These records should not be confused with isolated OH^* or CH^* radical observations.

Image Adjustments

The images presented herein have been adjusted through the use of background subtraction and grey scale adjustment as described in Appendix B. The adjustments isolated and clarified the viewing of the images on paper. For clarification of the interpretation of Schlieren and shadowgraph images see Appendix A.

2.3 Test Gases

This study examined stoichiometric methane-oxygen and hydrogen-oxygen. The gases were mixed in a separate 1.2m tall pressure vessel and left to mix for a minimum of 24 hours before an experiment. The minimum rest time of the gas was chosen to be larger than the time for 1-dimensional laminar diffusion layer to engulf the entire tank.

The channel was evacuated to below 80 Pa absolute pressure before filling with the test mixture. The test mixture was ignited using a high voltage spark obtained from a capacitive discharge of 1000 Joules, with deposition time of $2\mu s$. The first 70 cm of the channel was filled with a flame accelerator to help ensure that a detonation was initiated promptly. The flame accelerator, a series of wire mesh obstacles, ensures the initiation of the detonation in the minimum distance, details can be found in [32]. Velocity measurements from pressure gauges positioned prior to the obstacles permitted verification that self-sustained incident detonations were established.

For each gas mixture the lower experimental pressure limit for detonation initiation by the high voltage igniter (HVI) was determined to be approximately 10.34 kPa initial pressure and 6.89 kPa initial pressure for the hydrogen-oxygen and methane-oxygen re-

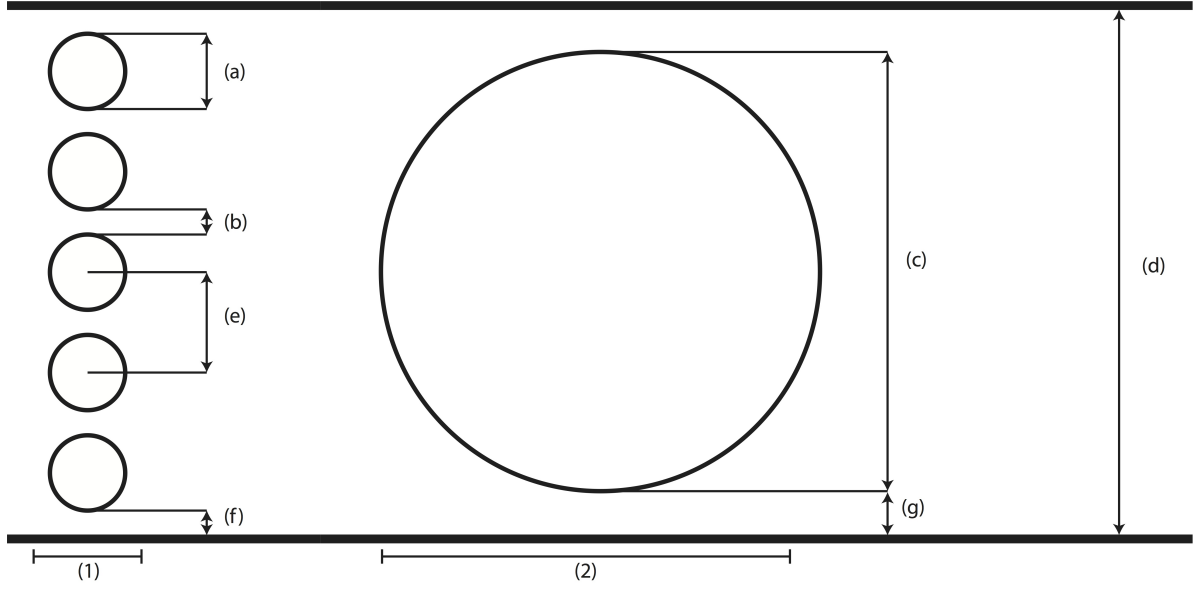


Figure 2.4: Schematic of the experimental obstacles: obstacle (1) (a) 30.5 mm, (b) 10 mm, (e) 40.5 mm, (f) 5 mm; obstacle (2) (c) 152 mm, (g) 25.6 mm; channel height (d) 203.2 mm. Obstacles were made of aluminium.

spectfully. All pressures are absolute. The upper pressure limits for the experiments in the glass walled sections were determined not to exceed an initial pressure of approximately $p_0 = 20$ kPa. This corresponded to the failure limit of the glass.

2.4 Obstacle Configuration

The obstacles used for this study were made of aluminium and placed in the center of the glass section. Two different obstacle configurations with the same blockage ratio were used. This allowed observation of the phenomenon at different scales, by a factor of five. An assembly of five cylinders (1), (a) 30.5 mm in diameter and spaced by (b) 10 mm is shown in Figure 2.4. A single larger cylinder (2), (c) 152 mm in diameter, was positioned centrally in the detonation channel, as shown in Figure 2.4. Experimental images of these configurations can be seen in chapters 3 and 4. The obstacles were placed in the channel and detonations impinged upon them and the resulting propagation observed.

Table 2.1: Cell sizes and gap size ratios for the experimental gas mixtures at the maximum pressure $P_o = 20$ kPa

	Cell Size (λ) [mm]	Gap Size (b) [mm]	b/λ at Max. Press.
Hydrogen-Oxygen $\phi = 1$	28.1	51.2	1.82
		10.0	0.35
Methane-Oxygen $\phi = 1$	22.29	51.2	2.29
		10.0	0.45

2.5 Cell Size

The experiments were conducted at pressures well below atmospheric pressure. The low pressure scales the size of the detonation structures to allow for better observations. Varying the initial pressure, p_0 , of the test mixture permitted the control of chemical sensitivity. The initial pressure changes the sensitivity of the combustion without significantly changing the shock dynamics.

The cell size (λ) is commonly used in place of pressure when reporting detonation behaviour as it better allows for comparison between geometries, pressures and gases. In the past for detonation failure using obstacles, as will be done in this work, the cell size (λ) is reported as a ratio with the gap size(b), as b/λ [30]. The higher the sensitivity, or the smaller the cell size, the more sensitive the chemical kinetics. Thus, the larger the b/λ ratio, the less likely detonation failure will occur in the wake of the obstacles [31].

This work reports on two fixed gap sizes with a constant blockage ratio. Staying within the safe operating limits, the range of cell sizes and gap size ratios for both experimental gas mixtures at the maximum pressure of $P_o = 20$ kPa is found in table 2.1. The cell sizes are calculated by interpolating the results reported by Denisov (1960) and Laberge (1993) from the Detonation Database [38].

Chapter 3

Hydrogen Results

The first series of results to be shown will be the results obtained using the hydrogen-oxygen mixture. The results are reported in four sections. First, single cylinder experiments are reported using the higher resolution Schlieren system to observe the near field, followed by the single cylinder results reported using the larger shadowgraph system. Shadowgraph records of the five cylinder experiments are then reported, observing the far field. In this Chapter select images and frames are displayed. For the full set of frames from the experiments here displayed see Appendix E.

3.1 Single Obstacle Experiments

3.1.1 Schlieren Records

When a detonation is initiated in the channel, it propagates through the hydrogen-oxygen mixture towards the obstacle. The detonation impinges upon the obstacle and diffracts around it, reflecting in the wake of the cylinder. As the pressure is increased inside the channel, the detonation cell size decreases. Thus, at higher initial pressures the b/λ ratio would be higher, indicating the gas mixture is less likely to fail, as mentioned in Section 2.5.

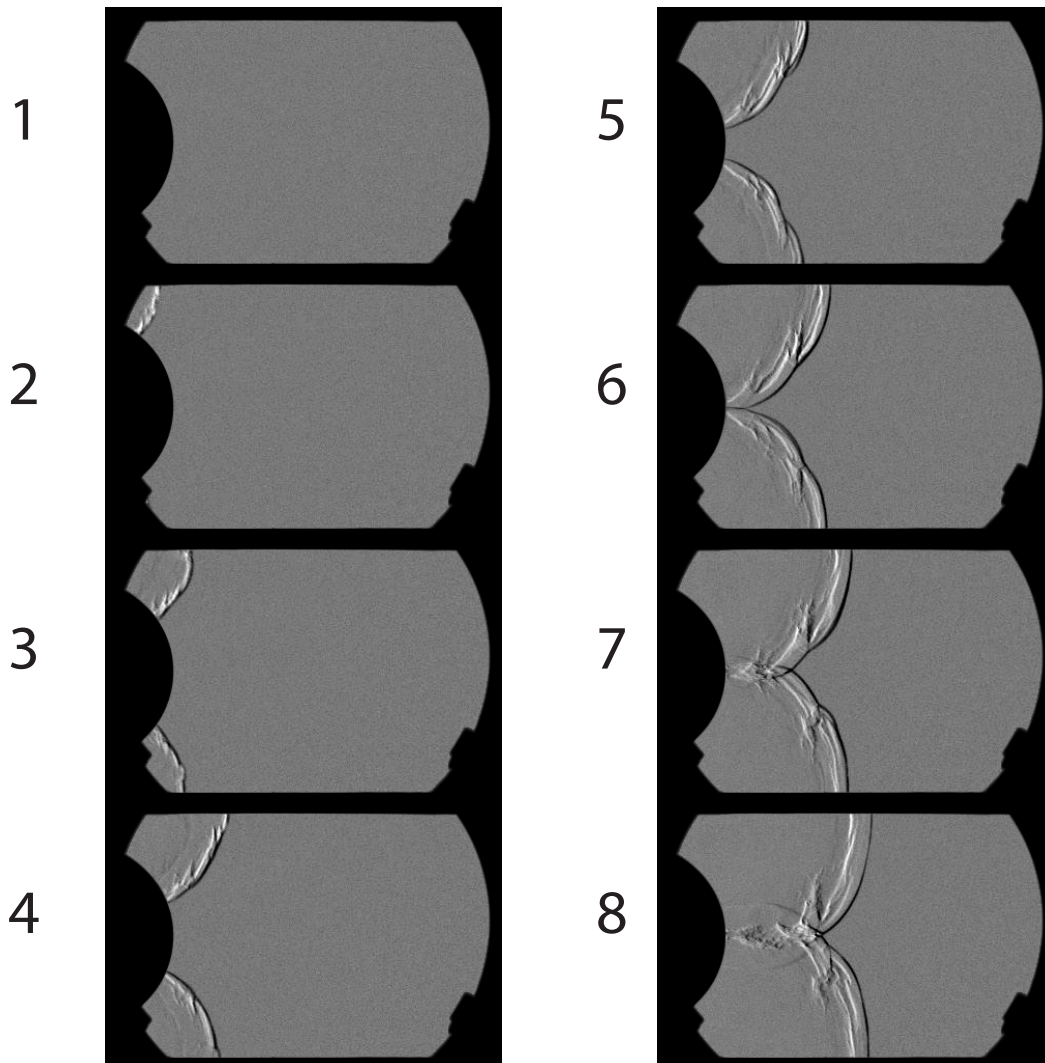
At the high pressure limit the detonation fails as it diffracts around the cylinder seen in Figure 3.1. This experiment was conducted at $p_0 = 12.4$ kPa which corresponds to $b/\lambda \simeq 1.32$. Frame 2 shows the detonation wave entering from the left, diffracting around the cylinder. The wave enters above and below the cylinder, frame 3, and continues moving towards the right. This shock-flame complex is composed of a leading shock

wave followed by a reaction zone as described in Chapter 1.1. The thick black line indicates the leading shock wave, followed by a period of high temperature and pressure which is terminated by a thicker and fainter white line indicating the drop in density, the reaction zone.

As the shock-flame complex continues downstream, in Figure 3.1, the distance between the lead shock wave and the reaction zone increases. Frames 6 through 8 show the initial stages of the transitional shock reflection, beginning with a regular shock reflection.

As the shock-flame complex continues to reflect in frame 9 of Figure 3.2, the Mach stem becomes apparent, indicative of this type of shock reflection. At these conditions the shock reflection directly initiates a detonation wave, seen in frame 10. The detonation wave is identified qualitatively by the thin structure and faint appearance of a cellular structure with small trailing transverse waves. With the small field of view, the interpretation is difficult in these images. Qualitatively this is identified as a detonation by the large and sudden jump in the centreline velocity of the lead shock wave, seen in Figure 3.3.

The velocity profile for the above experiment is plotted in Figure 3.3. The speed of the wavefront in the x-direction is calculated using the sequential frames and known interframe time. The uncertainty measure is defined as the average uncertainty from each point in the experiment and is described in Appendix D.



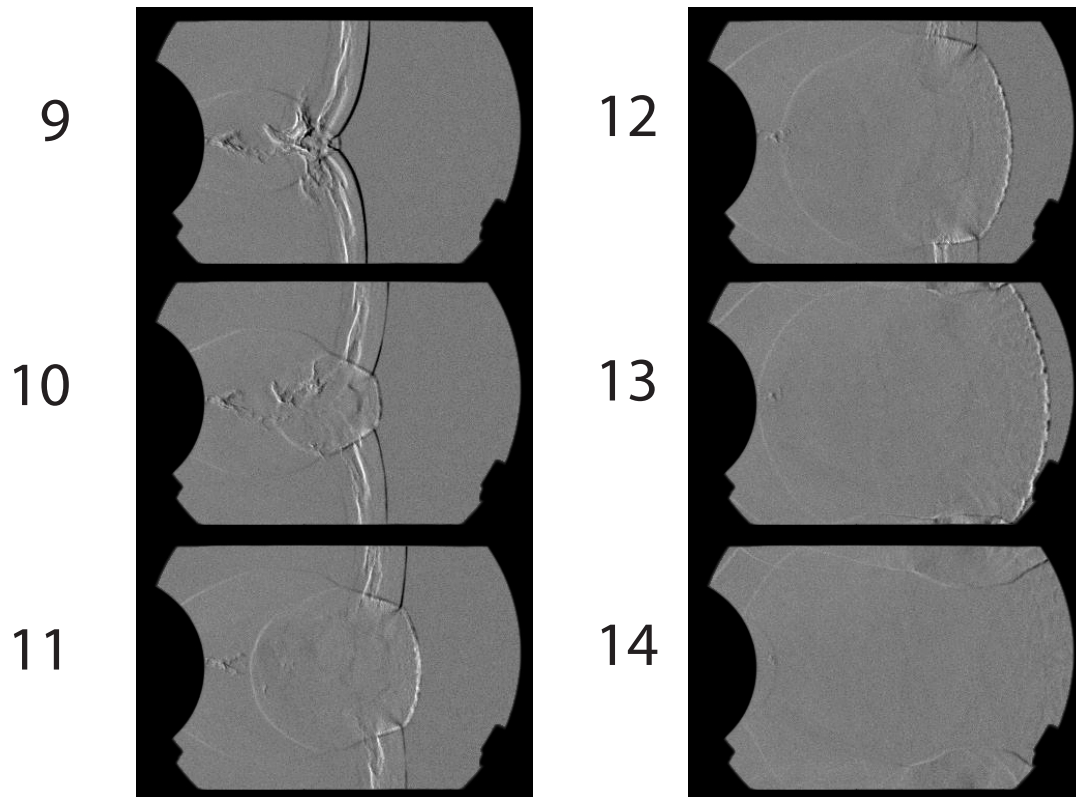


Figure 3.2: Schlieren record of hydrogen-oxygen detonation failure around the single cylinder and reactive reflection at $p_0 = 12.4$ kPa. Recorded at $11.62 \mu\text{s}$ interframe time, $0.91 \mu\text{s}$ exposure, 86058.5 fps. The full experimental record can be found in Figure E.8 & E.9.

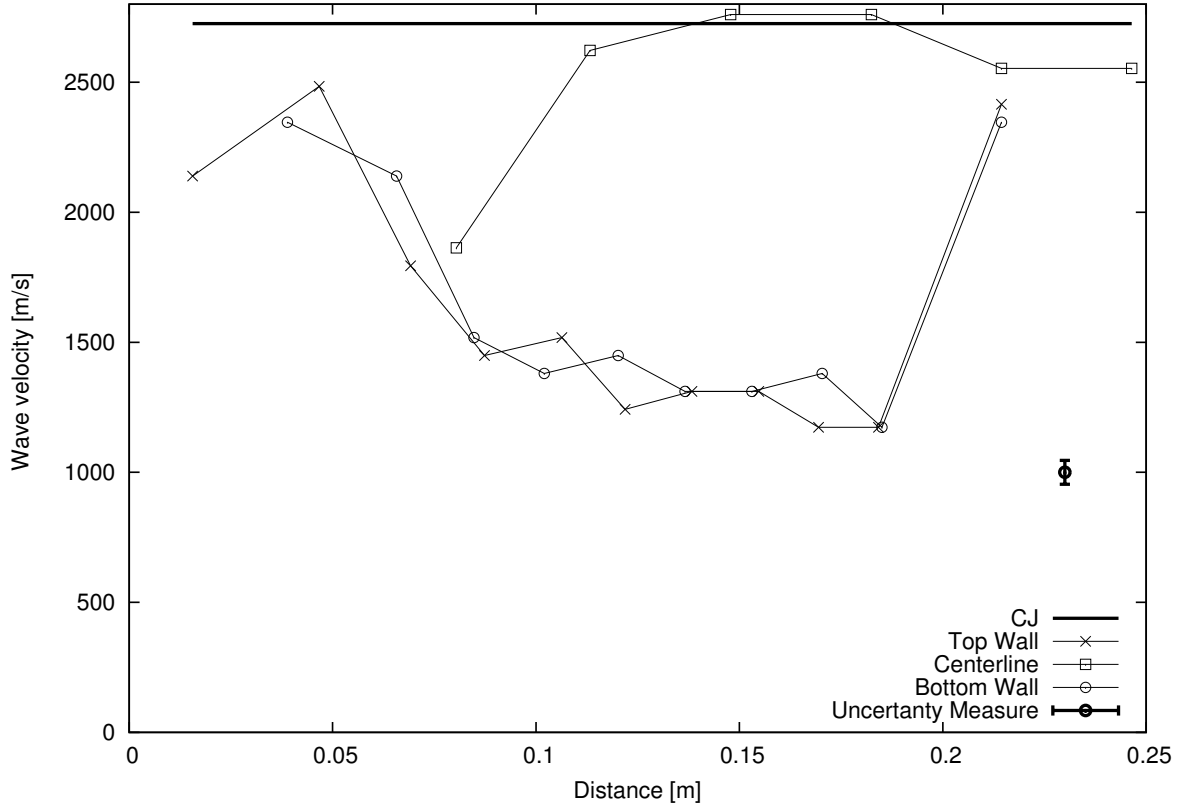


Figure 3.3: Velocity record from the above Schlieren images of hydrogen-oxygen $p_0 = 12.4$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

As the pressure is lowered, the behaviour is observed to change. A separate experiment, $p_0 = 11.0$ kPa and $b/\lambda \simeq 1.14$, seen in Figure 3.4 shows the evolution of the reacted pocket of gas behind the Mach stem. The velocity of the lead shock wave measured in the x-direction is seen in Figure 3.5 The growth of the hot spot, often referred to as *keystone structure*, observed here starting at early times, seen in frame 7. As the pocket grows, some Kelvin-Helmholtz instability can be seen along the shear layer in the reacted pocket. The contact surface between un-reacted and reacted gas behind the Mach stem appears to be quite laminar throughout the growth and evolution of the pocket of gas.

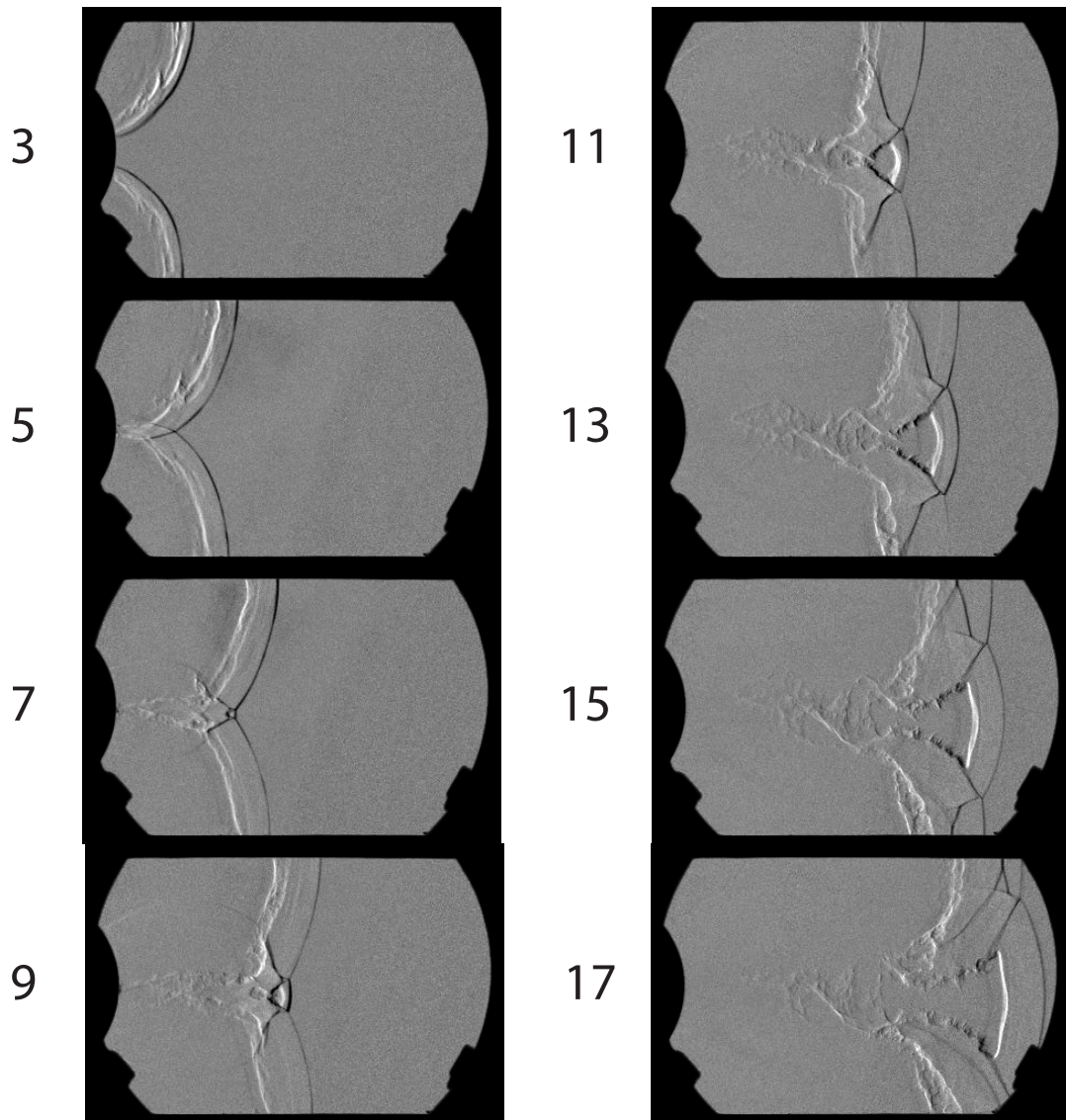


Figure 3.4: Schlieren record of hydrogen-oxygen detonation failure around the single cylinder and reactive reflection at $p_0 = 11.0$ kPa. Recorded at $11.62 \mu\text{s}$ interframe time, $0.91 \mu\text{s}$ exposure, 86058.5 fps, the full experimental record can be found in Figure E.10.

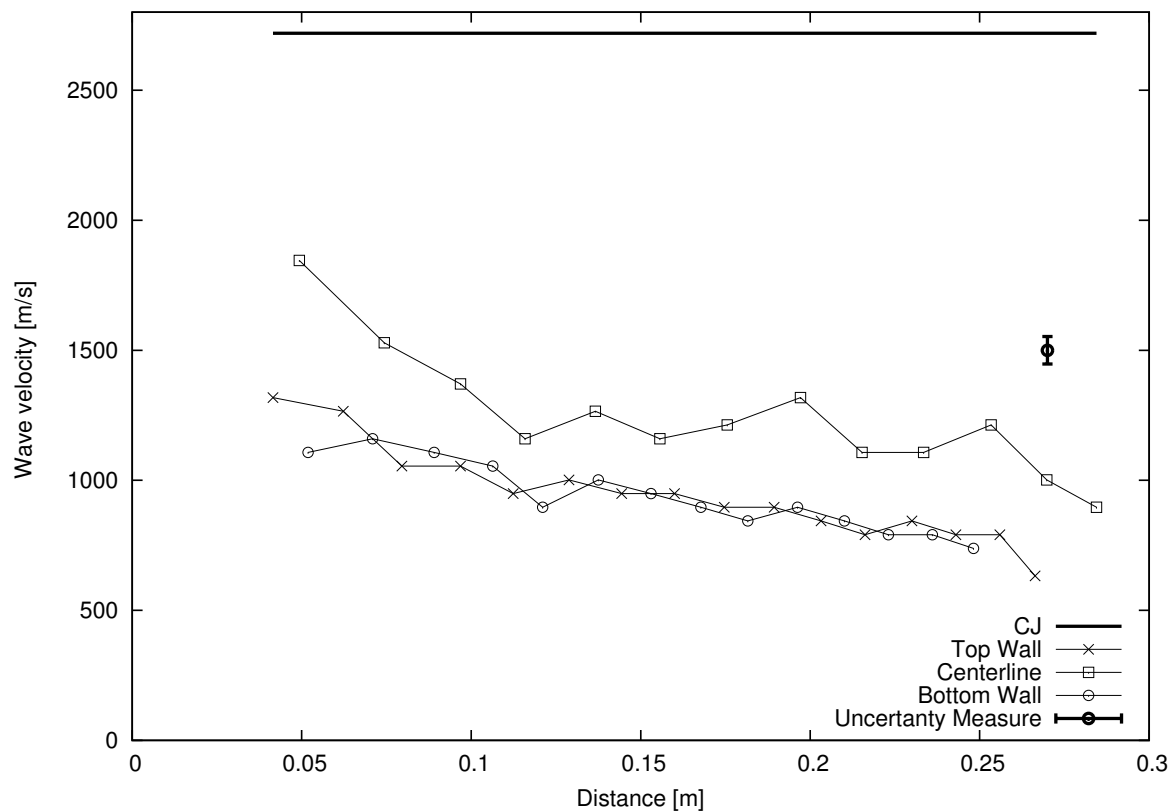


Figure 3.5: Velocity record from the above Schlieren images of hydrogen-oxygen $p_0 = 11.0$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

The lowest pressure regime observed in Figure 3.6 shows the results with an initial pressure of $p_0 = 10.3$ kPa and a sensitivity of $b/\lambda \simeq 1.07$. The velocity of the lead shock wave measured in the x-direction is seen in Figure 3.7. As the pressure and thus the sensitivity is lowered, an un-reactive reflection is observed.

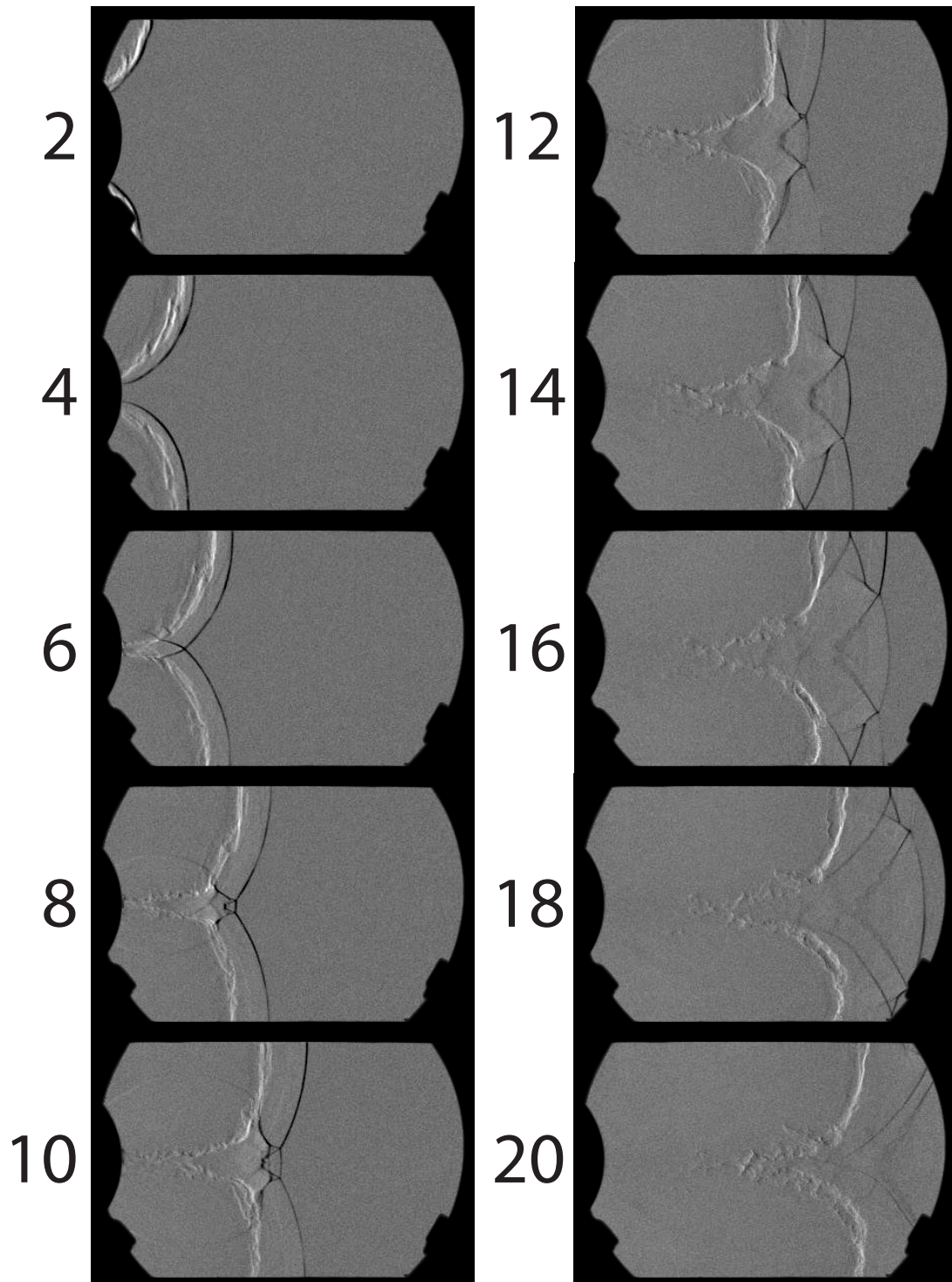


Figure 3.6: Shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder and un-reactive reflection at $p_0 = 10.3$ kPa. Recorded at $11.62 \mu\text{s}$ interframe time, $0.91 \mu\text{s}$ exposure, 86058.5 fps, the full experimental record can be found in Figure E.11.

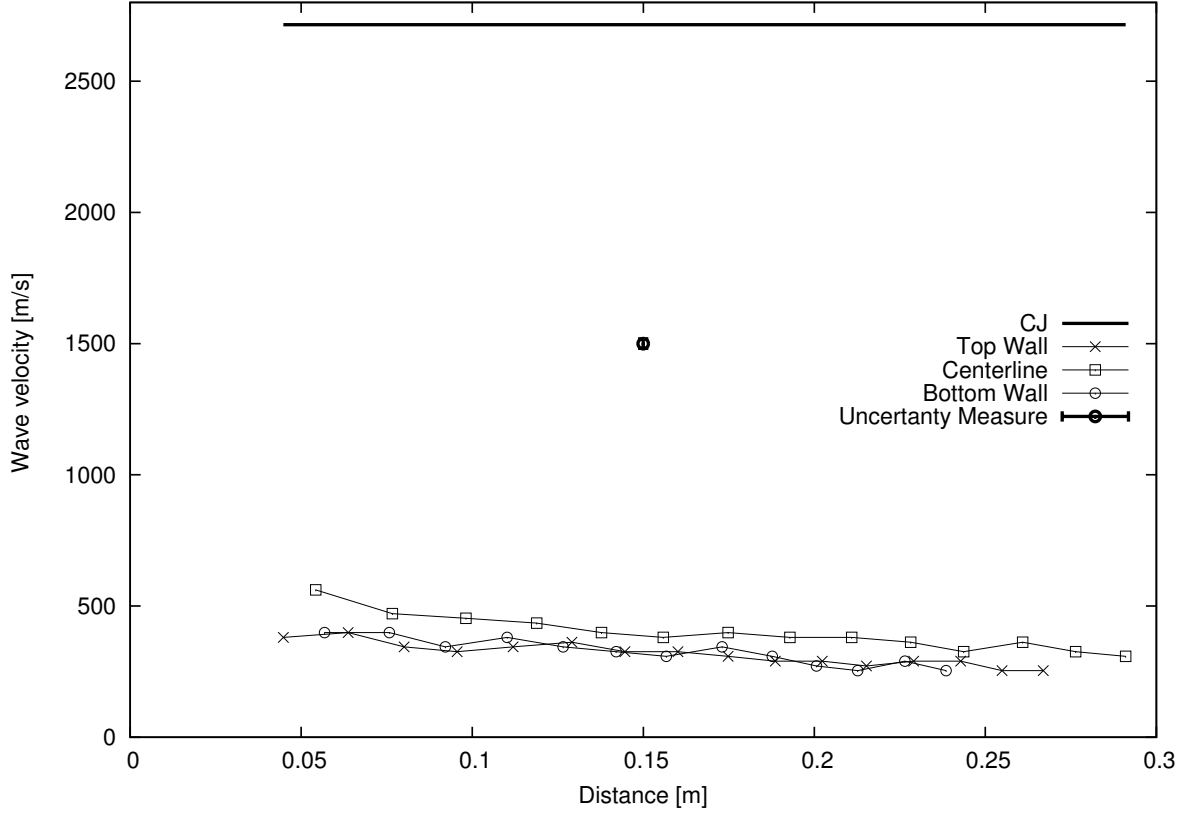


Figure 3.7: Velocity record from the above Schlieren images of hydrogen-oxygen $p_0 = 10.3$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

3.1.2 Shadowgraph Records

Examining experiments conducted with the large scale shadowgraph system shows the same behaviour as in Figures 3.1-3.6. Using the shadowgraph system to observe the far field, Figures 3.8-3.9 show direct detonation initiation at approximately $P_0 = 14.2$ kPa. This corresponds to a $b/\lambda \simeq 1.66$. Above this pressure the Mach stem would immediately transition to a detonation. The diffraction around the cylinder would be unable to adequately attenuate the wave to produce a fast flame.

The velocity profile extracted from this experiment, seen in Figure 3.10, shows the velocity jumping closer to the CJ velocity. This pressure region is identified as the critical upper pressure regime, as seen with the Schlieren system, Figure 3.1. Below this pressure, the reflection is reactive but does not initiate a detonation.

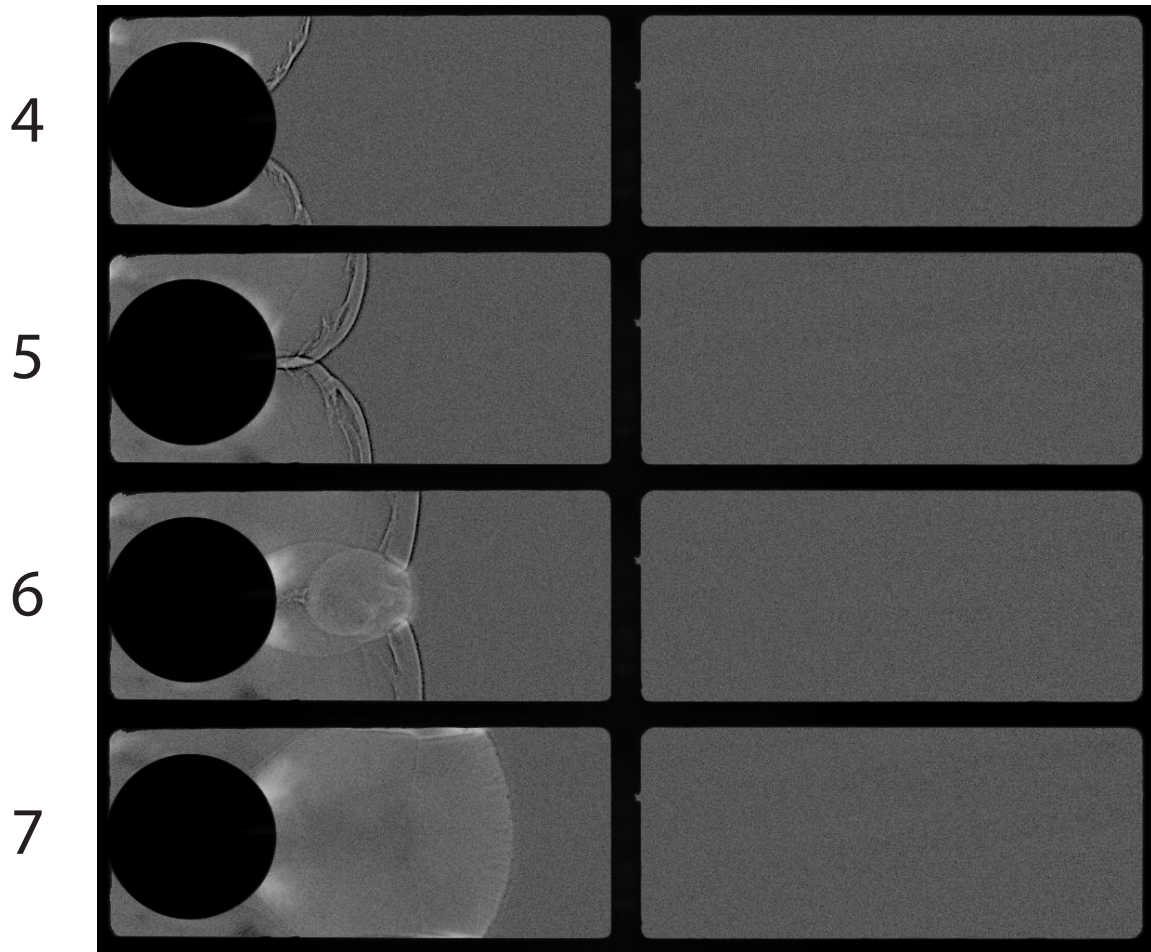


Figure 3.8: Shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder and subsequent detonation initiation upon reflection. $p_0 = 14.2$ kPa. Recorded at $42.74 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 23400.02 fps. The full experimental record can be found at Figure E.5.

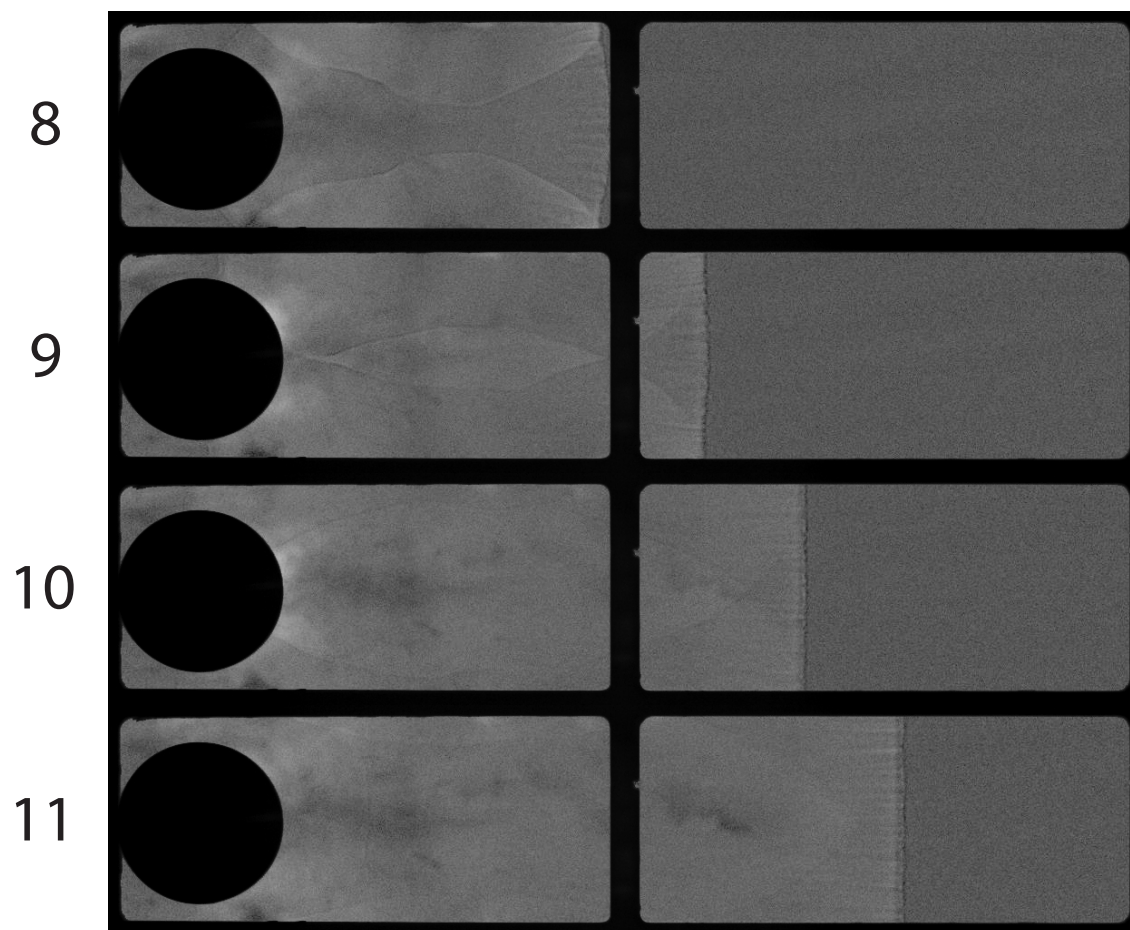


Figure 3.9: Shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder and subsequent detonation initiation upon reflection. $p_0 = 14.2$ kPa. Recorded at $42.74 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 23400.02 fps. The full experimental record can be found at Figure E.5.

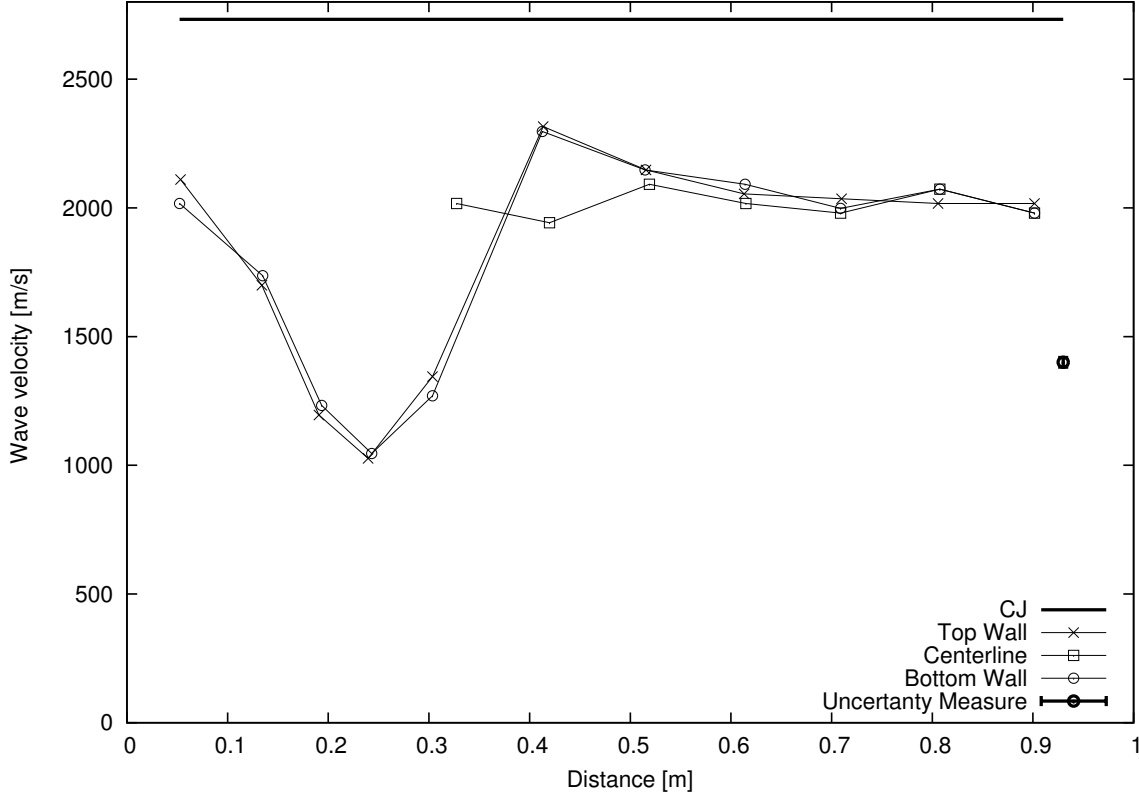


Figure 3.10: Velocity record from the above shadowgraph images of hydrogen-oxygen $p_0 = 14.2$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

Figures 3.11 & 3.12 show an experiment exhibiting this behaviour with an initial pressure of $p_0 = 13.8$ kPa and $b/\lambda \simeq 1.66$. The shock-shock reflection immediately following the diffraction around the cylinder is unable to initiate a detonation but it is able to create a hot spot, as seen in frame 6 as a pocket of reacted gas. This keystone structure has ignited and the Mach stem expands to fill the channel.

As the wave continues to propagate to the left in Figure 3.12, the lead shock quickly becomes a planar shock wave and the reaction zone continues to lag further and further behind the lead shock. Two faint transverse shock waves generated from the initial reactive reflection are visible until frame 16.

The velocity profile, Figure 3.13, shows the velocity measured at each location collapsing into a single curve, indicative of the planar lead shock wave. After the reactive reflection, noted by the increased velocity of the centreline velocity ($\simeq 0.2$ m) and the first wall reflections ($\simeq 0.4$ m), the entire wave begins to decay and the velocity slowly

decreases as the wave propagates.

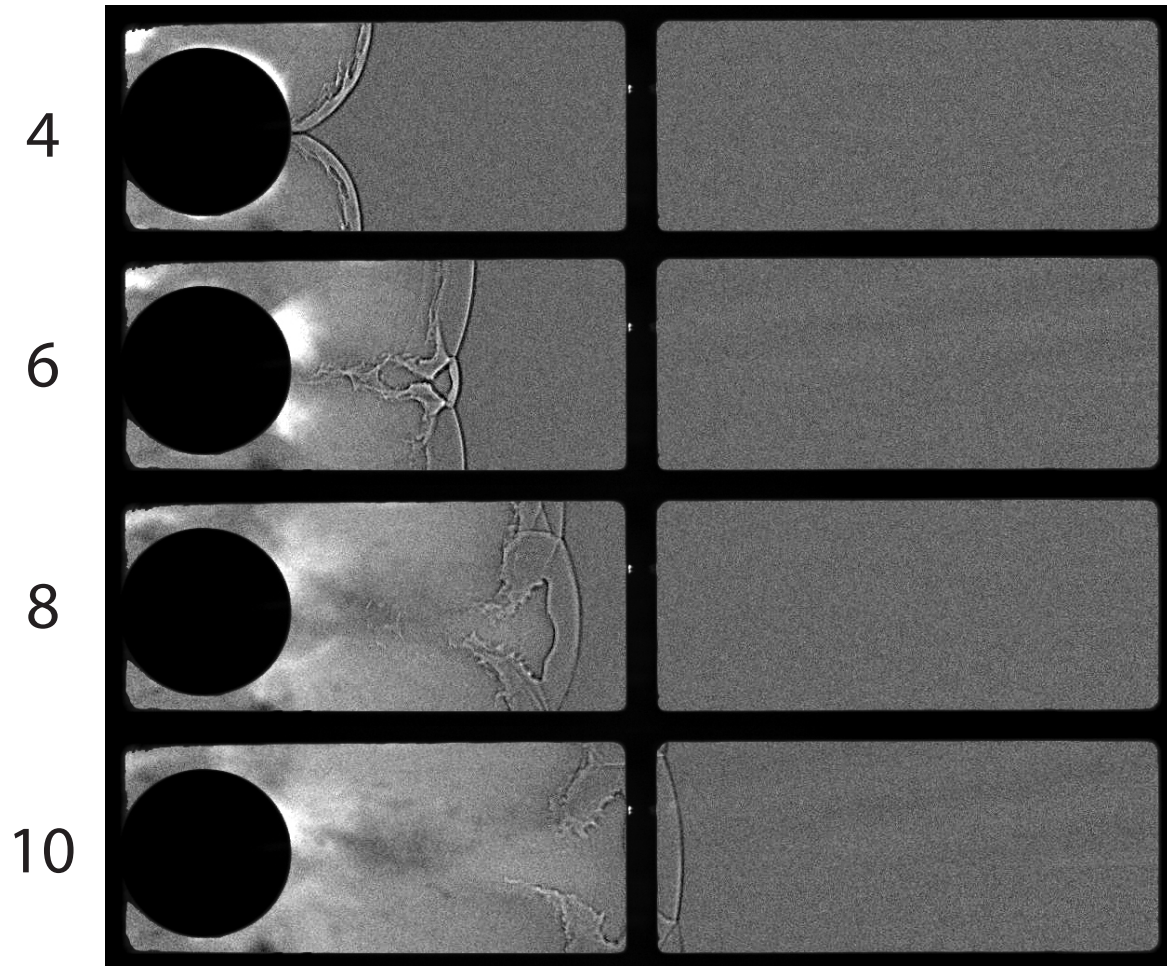


Figure 3.11: Shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder, reactive reflection and subsequent wave decay at $p_0 = 13.8$ kPa. Recorded at $42.74 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 23400.02 fps. The full experimental record can be found at Figure E.6.

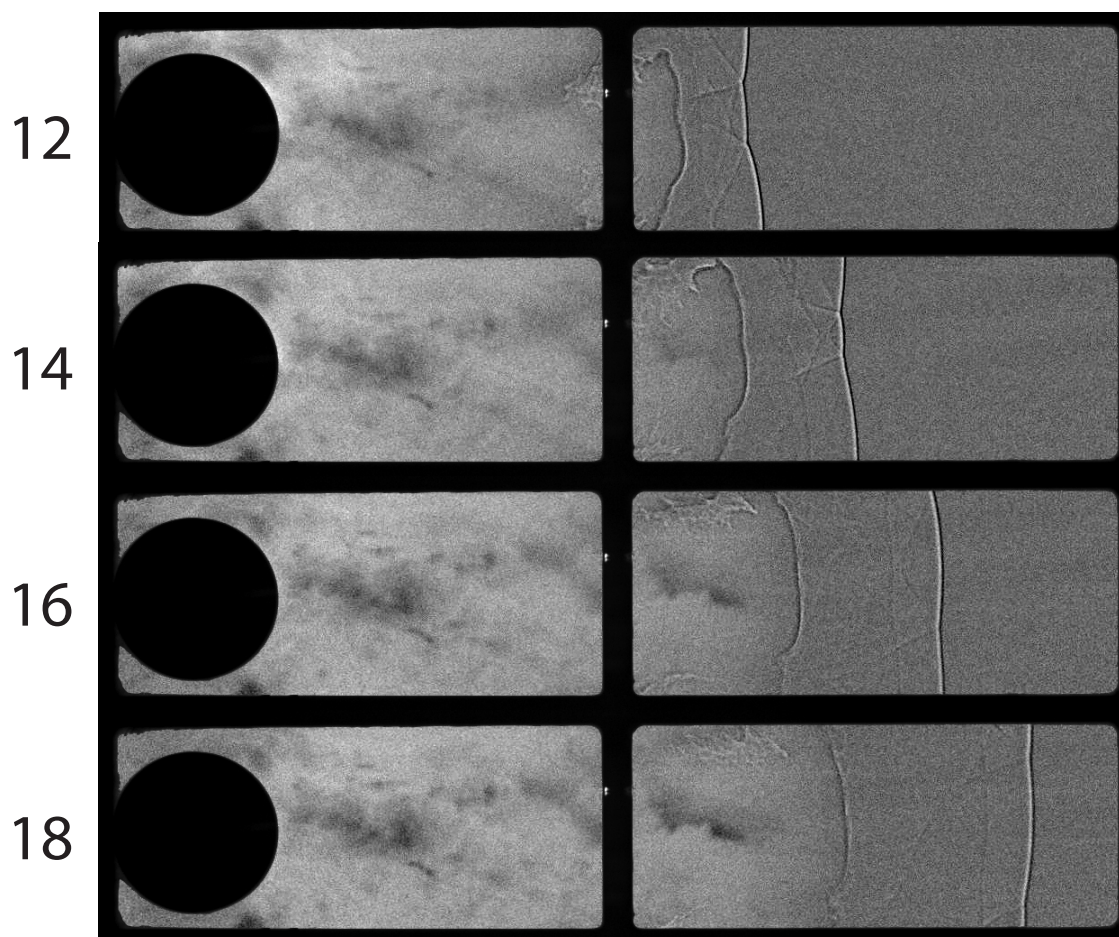


Figure 3.12: Shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder, reactive reflection and subsequent wave decay at $p_0 = 13.8$ kPa. Recorded at $42.74 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 23400.02 fps. The full experimental record can be found at Figure E.6.

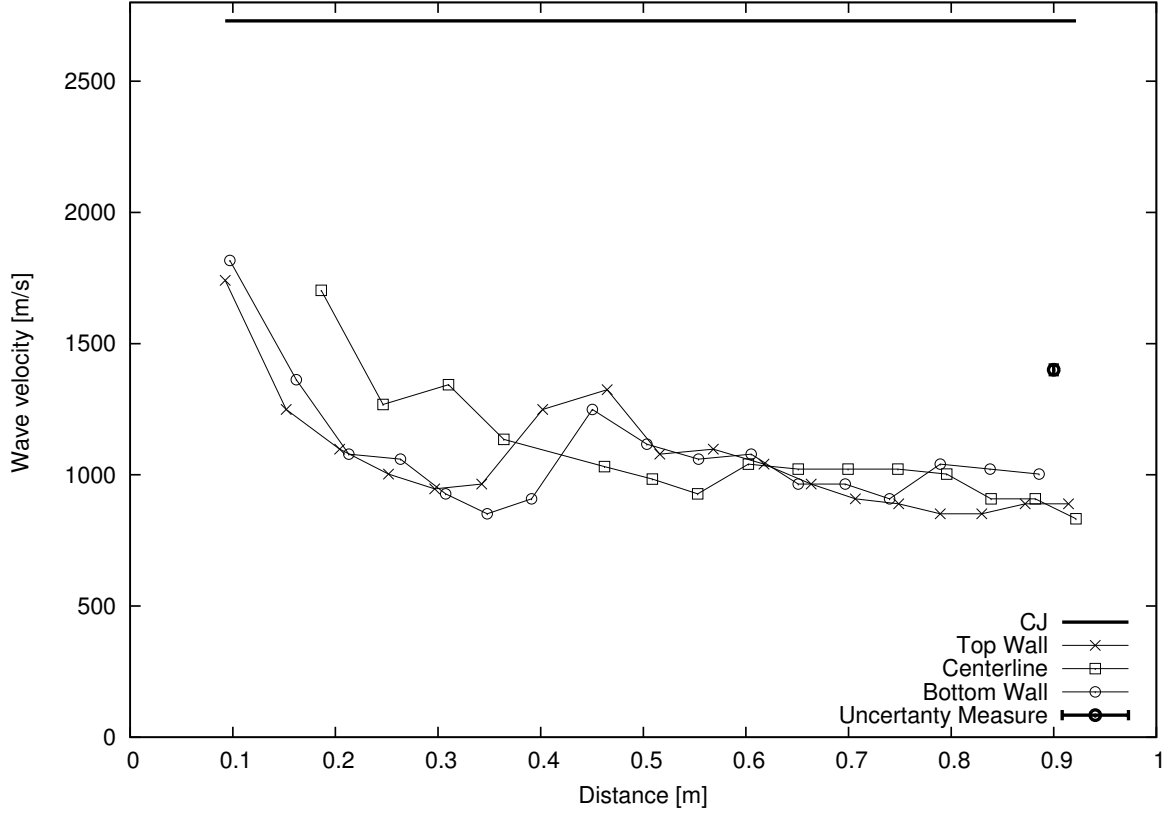


Figure 3.13: Velocity record from the above shadowgraph images of hydrogen-oxygen $p_0 = 13.8$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

3.2 Five Obstacle Experiments

3.2.1 Shadowgraph Records

The tests here conducted used five equally spaced metal obstacles described in section 2.4. The incoming detonation again enters from the left and impinges upon the obstacles. The evolution of the resulting waves are monitored using shadowgraph imaging, as done before.

Experiments conducted near the upper pressure limit of the channel using the five obstacles showed detonation decoupling around the obstacle. The highest pressure tested was $p_0 = 18.6$ kPa. These conditions correspond to $b/\lambda \simeq 0.86$. Select frames displaying the behaviour of the experiments are seen in Figures 3.14 & 3.15.

Here in Figure 3.14, the detonation is entering from the left in frame 2, and diffracting in the wake of the cylinders in frame 3. The keystone structures seen in the wake of the single cylinder, are visible in the fourth frame. The transverse waves generated by the transitional shock reflections give rise to the second generation of hot spots in the fifth frame. A single hot spot is created in the third generation in the eighth frame.

No new generation of hot spots is created as the wave continues in Figure 3.15. The wave develops into a planar shock wave followed by an ever-trailing flame. Frame 18 shows the beginning of an anomalous perturbation in the lead shock wave, leading to increased combustion rates and a transverse wave travelling across the shock front from top to bottom. This is believed to be an imperfection on the surface of a pressure sensor located along the top wall which could have led to a small shock reflection and hotspot.

The velocity profile, Figure 3.16, shows the velocity of the lead shock wave along the centrelines of each of the five cylinders. After the initial velocity drop in the wake of the cylinder, the velocity continues to decay along the length of the channel.

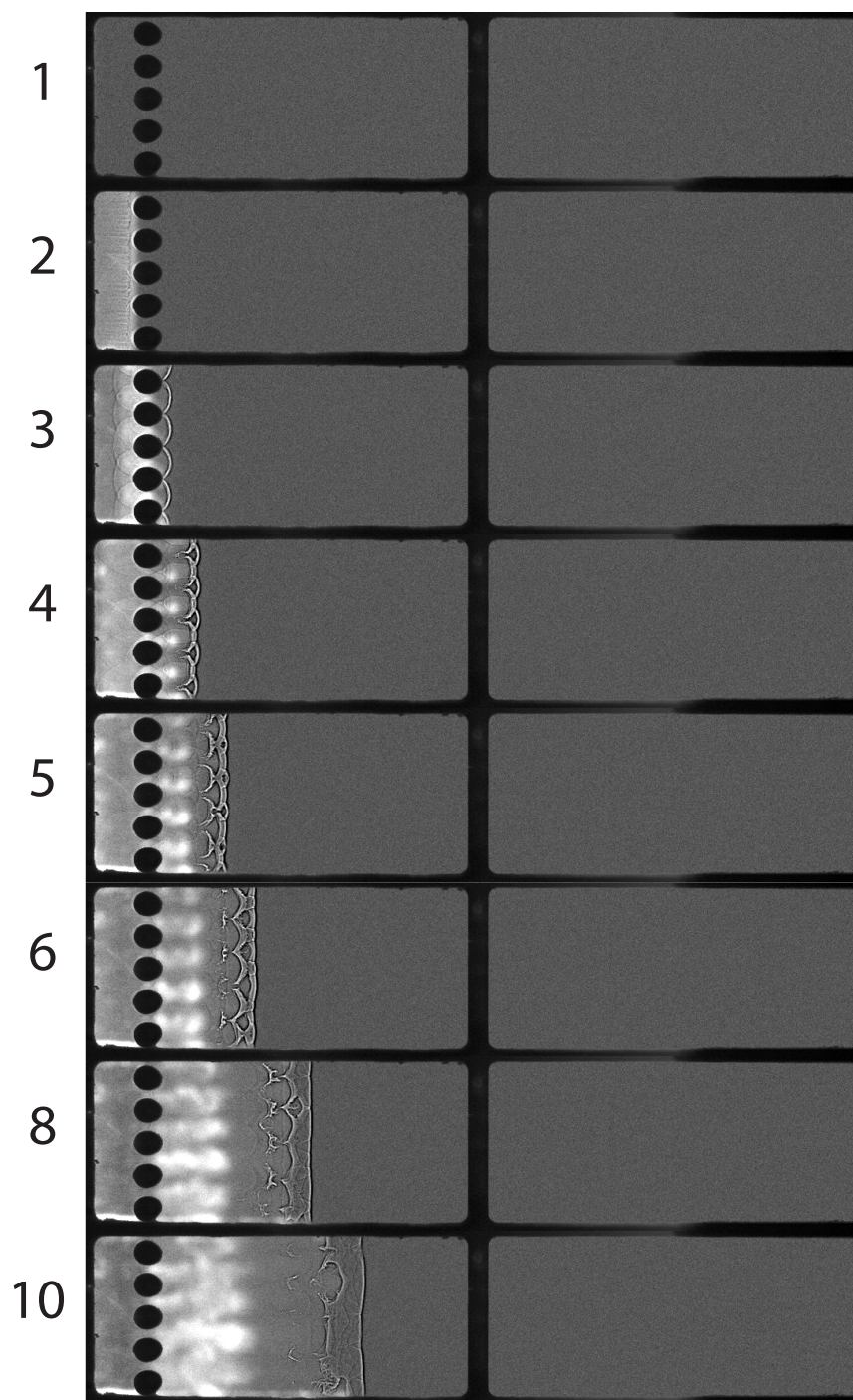


Figure 3.14: Shadowgraph images illustrating the detonation failure at the maximum pressure tested in $2\text{H}_2\text{-O}_2$, $p_0 = 18.6$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 46040.5 fps, the full record can be found in Figures E.1 & E.2.

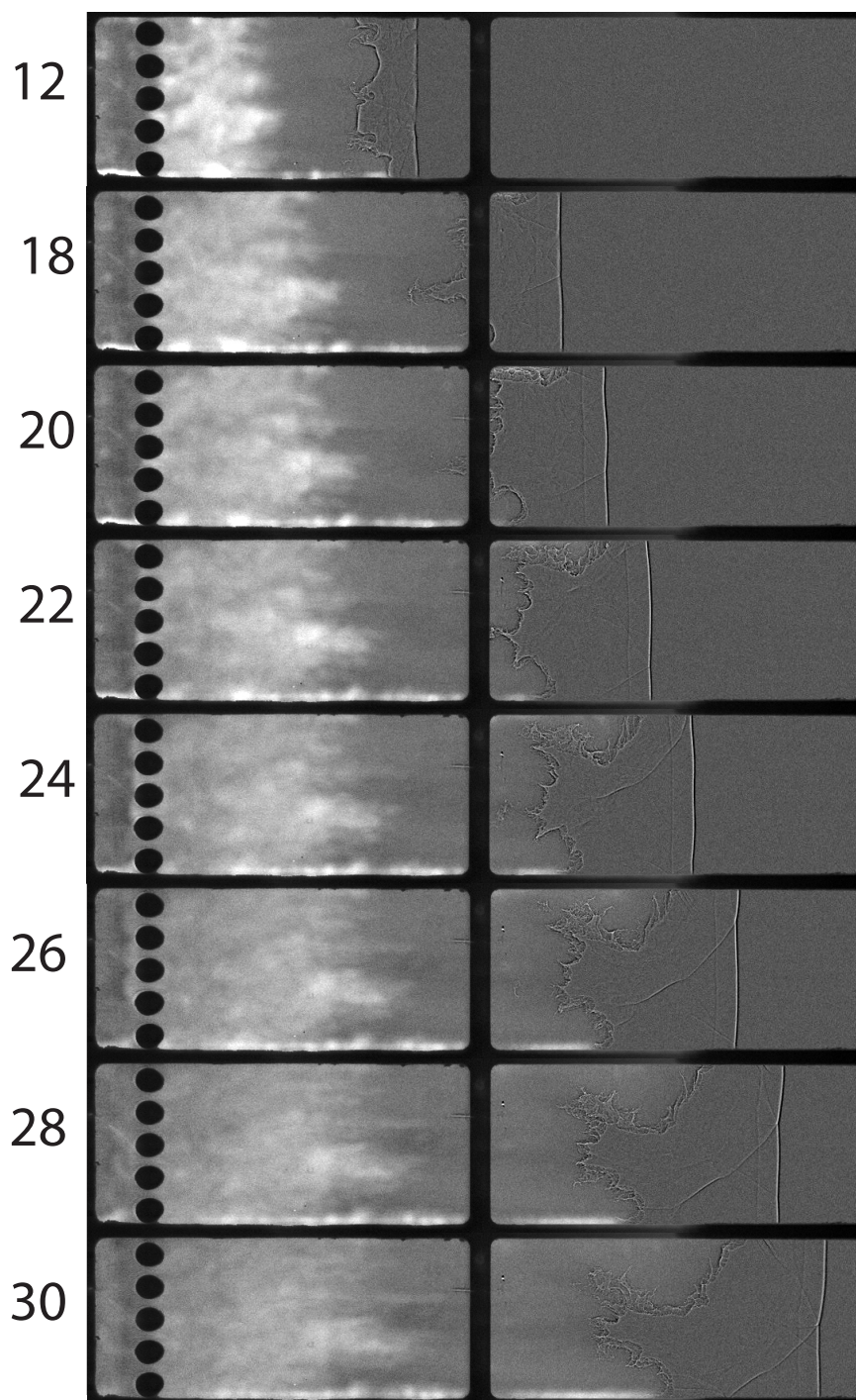


Figure 3.15: Shadowgraph images illustrating the detonation failure at the maximum pressure tested in $2\text{H}_2\text{-O}_2$, $p_0 = 18.6$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 46040.5 fps, the full record can be found in Figures E.1 & E.2.

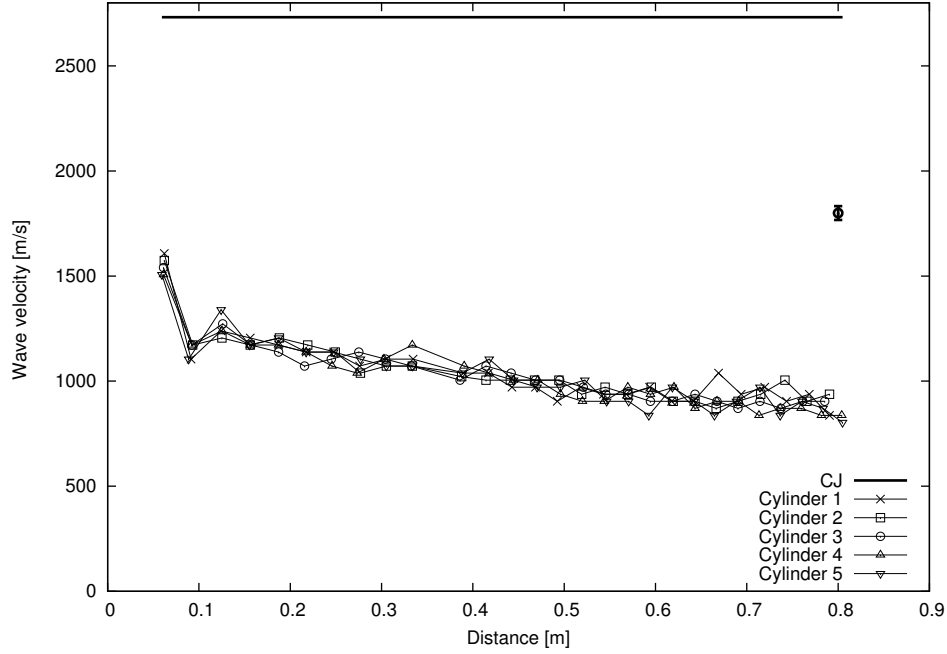


Figure 3.16: Velocity record from the above shadowgraph images of hydrogen-oxygen $p_0 = 18.6$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

The behaviour described above generally represents the pervasive behaviour of the experiment in hydrogen-oxygen. Another experiment is seen in Figures 3.17 & 3.18, done at a slightly lower pressure. This experiment was conducted with an initial pressure of $p_0 = 17.2$ kPa. These conditions correspond to a $b/\lambda \simeq 0.54$.

This series of shadowgraph images, Figure 3.17, shows the initial detonation entering on the left, the detonation interaction with the obstacles, subsequent diffraction and formation of the shock-flame structure, followed by continual decay of the wave. The initial wave diffraction around the cylinders causes local wave attenuation around the downstream side of the obstacles. This attenuation decouples the lead shock and reaction zone of the detonation. The shock diffraction curves the wave resulting in transitional Mach shock reflections in the wake of the cylinders. These shock-shock reflections increase the temperature and pressure behind the reflected waves, causing the first generation of hotspots behind the Mach stem.

This hotspot formation, and lack of detonation initiation, is consistent with the mechanism reported by Radulescu & Maxwell from their numerical simulations, as well as previous experiments performed by Lee & Papyrin, reported in [30]. This behaviour is

consistent with the results of acetylene-oxygen-argon mixtures after obstacle interaction from [30].

After the reflection, the Mach stem resulting from the formation of the keystone structure overtakes the original shock, resulting in a second series of shock-shock interactions. The second set of reflections leads to the second generation of hotspots; however, this new keystone structure is smaller and does not significantly amplify the new Mach stem. As a result from the weaker Mach stem, the third reflection is unable to create a hotspot. As the second generation of Mach stems grow and overtake the wavefront, the waves begin to form a planar wavefront, seen in Figure 3.18. The transverse waves continue to attenuate and as a planar wavefront is formed, the reaction zone continually lags further and further behind.

From the sequential frames, the shock speed evolution has been defined along the straight behind the center of each cylinder, seen in Figure 3.19. After the interaction with the obstacles, the wave is symmetrically attenuated as it diffracts. The first velocity jump corresponds to the first keystone structure which coherently increases the wave speed before a planar wave is formed and decay begins.

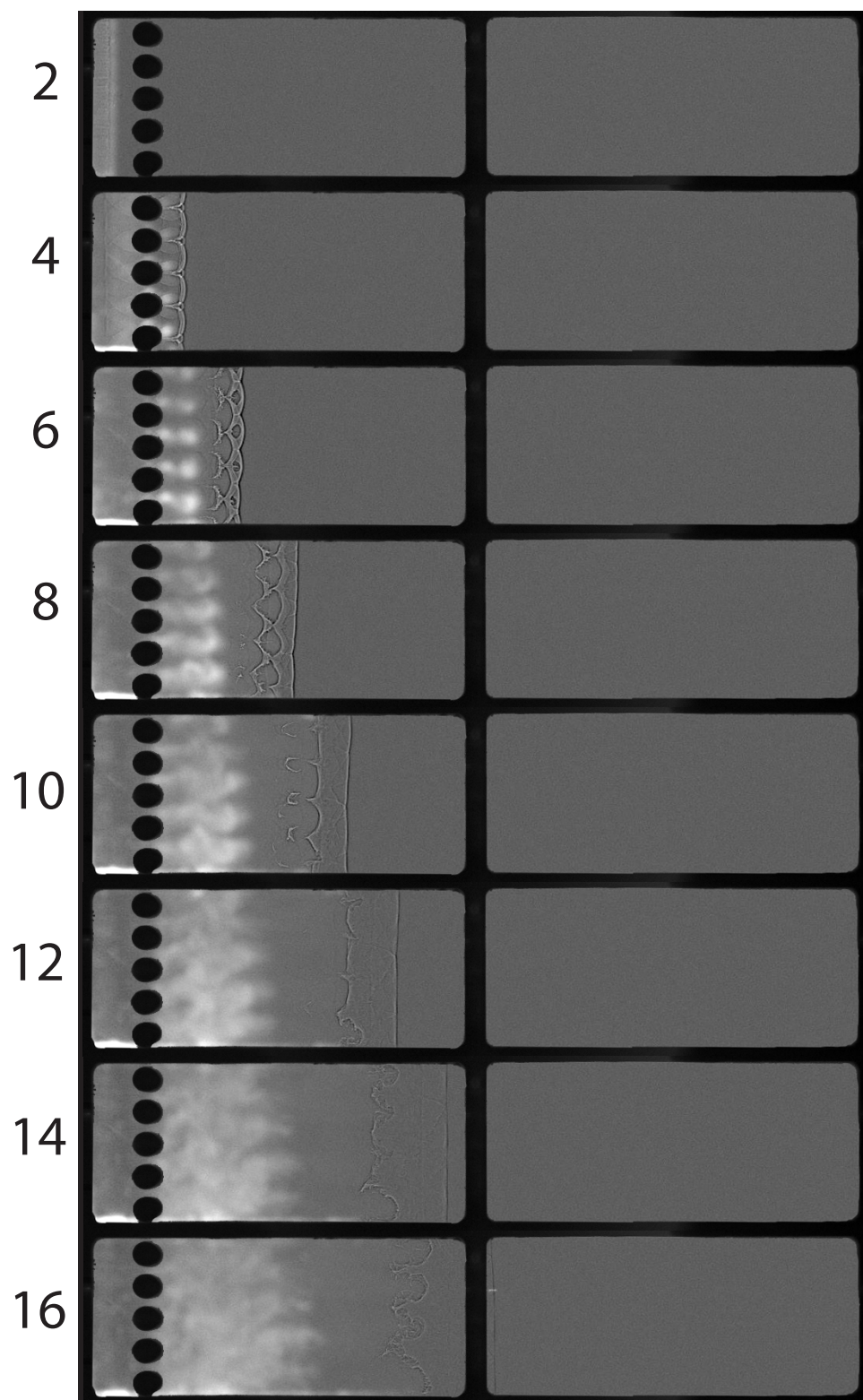


Figure 3.17: Shadowgraph images illustrating the decay of the fast flame in 2H₂-O₂, $p_0 = 17.2$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 46040.5 fps, the full experimental record can be found in Figures E.3 & E.4.

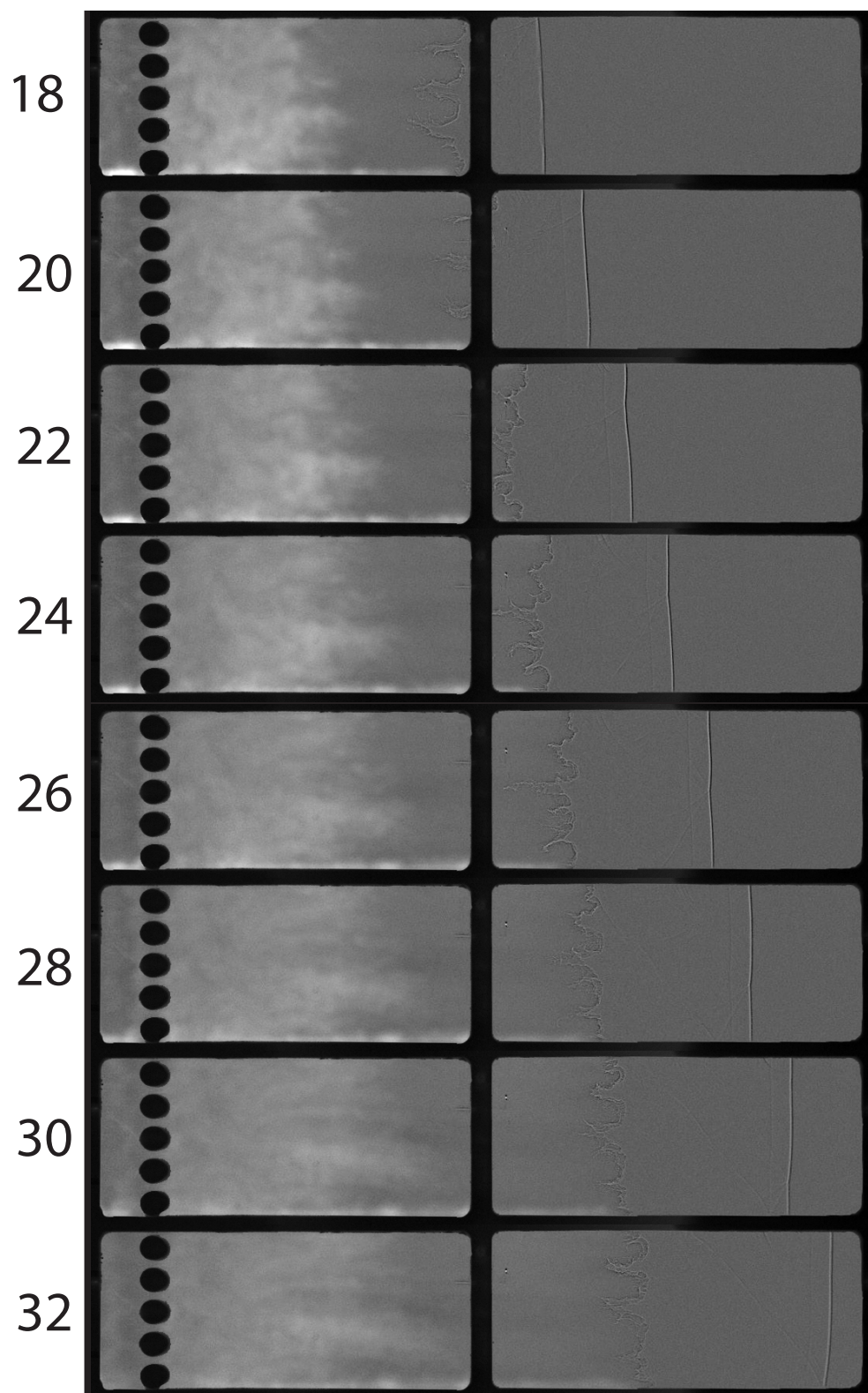


Figure 3.18: Shadowgraph images illustrating the decay of the fast flame in $2\text{H}_2\text{-O}_2$, $p_0 = 17.2$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 46040.5 fps, the full experimental record can be found in Figures E.3 & E.4.

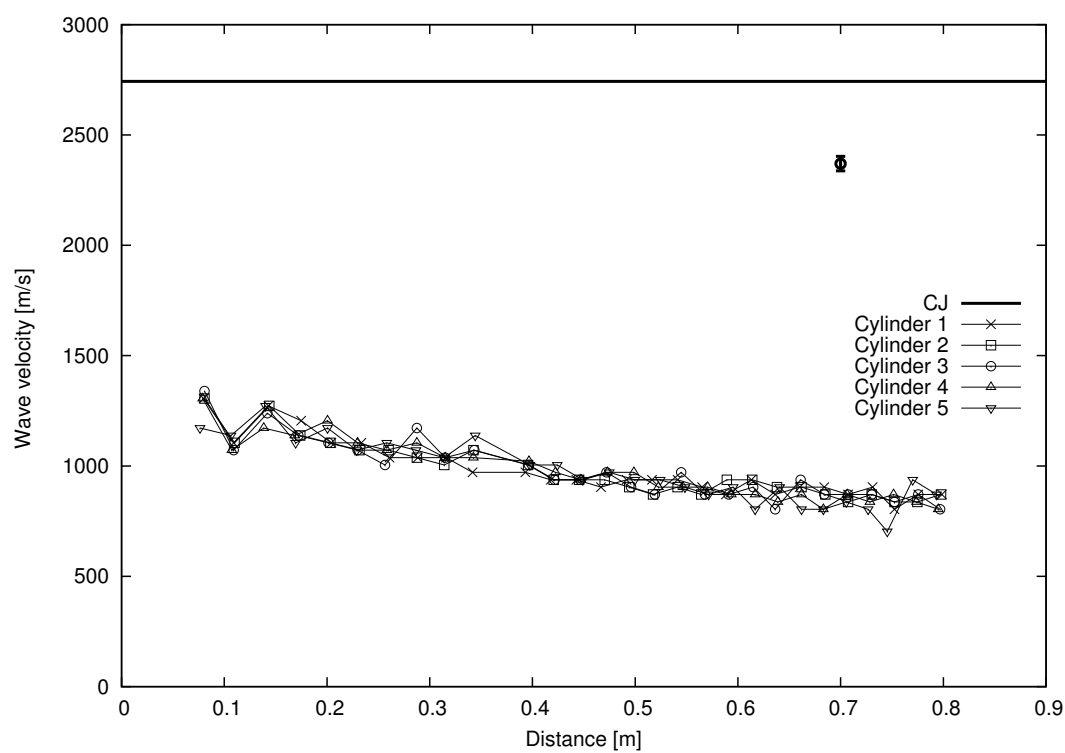


Figure 3.19: Velocity record from the above shadowgraph images of hydrogen-oxygen $p_0 = 17.2$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

Chapter 4

Methane Results

This Chapter examines the results obtained using the methane-oxygen mixture. The results are reported in five sections. First, single cylinder experiments are reported using the higher resolution Schlieren system to observe the near field, followed by the single cylinder results reported using the larger shadowgraph system, as well as self-luminous records. The five cylinder experiments are then reported using the Schlieren followed by the observations with the shadowgraph to observe the far field. In this Chapter select images and frames are displayed. For the full set of frames from the experiments here displayed see Appendix F.

4.1 Single Obstacle Experiments

4.1.1 Schlieren Records

To gain an understanding of the reflection dynamics in methane-oxygen, the higher resolution Schlieren system was used to focus upon the very reproducible first shock-shock reflection in the wake of the single cylinder. The experiments shown here were conducted with Rohit Bhattacharjee. Figure 4.1 shows the reactive reflection.

Figure 4.1 shows the development of a reactive shock-shock reflection just above the minimum sensitivity required for a reactive reflection, $p_0 = 8.3$ kPa and $b/\lambda \simeq 0.73$. As the failing detonation wave enters from the left, frame 6 shows the decoupled shock-flame complex during the regular reflection phase of the transitional shock reflection process just prior to the formation of the Mach stem. The Mach stem develops beginning in frame 8. As the area expands, frame 12, a flame acceleration occurs where the two slip

lines meet. By frame 14 this flame jet penetrates into the region behind the Mach stem and begins to engulf the region. Frame 16 shows the reactive pocket engulfing most of the region and transmitting transverse pressure waves, following the transverse wave. As the fast flame exits the frame, the large coherent structures along the slip line become apparent, evident of the Kelvin-Helmholtz instability.

The velocity profile, seen in Figure 4.2, shows the higher velocity of the centreline. Near the end of the visualization, when the reaction envelops the region behind the Mach stem, the velocity jump is apparent.

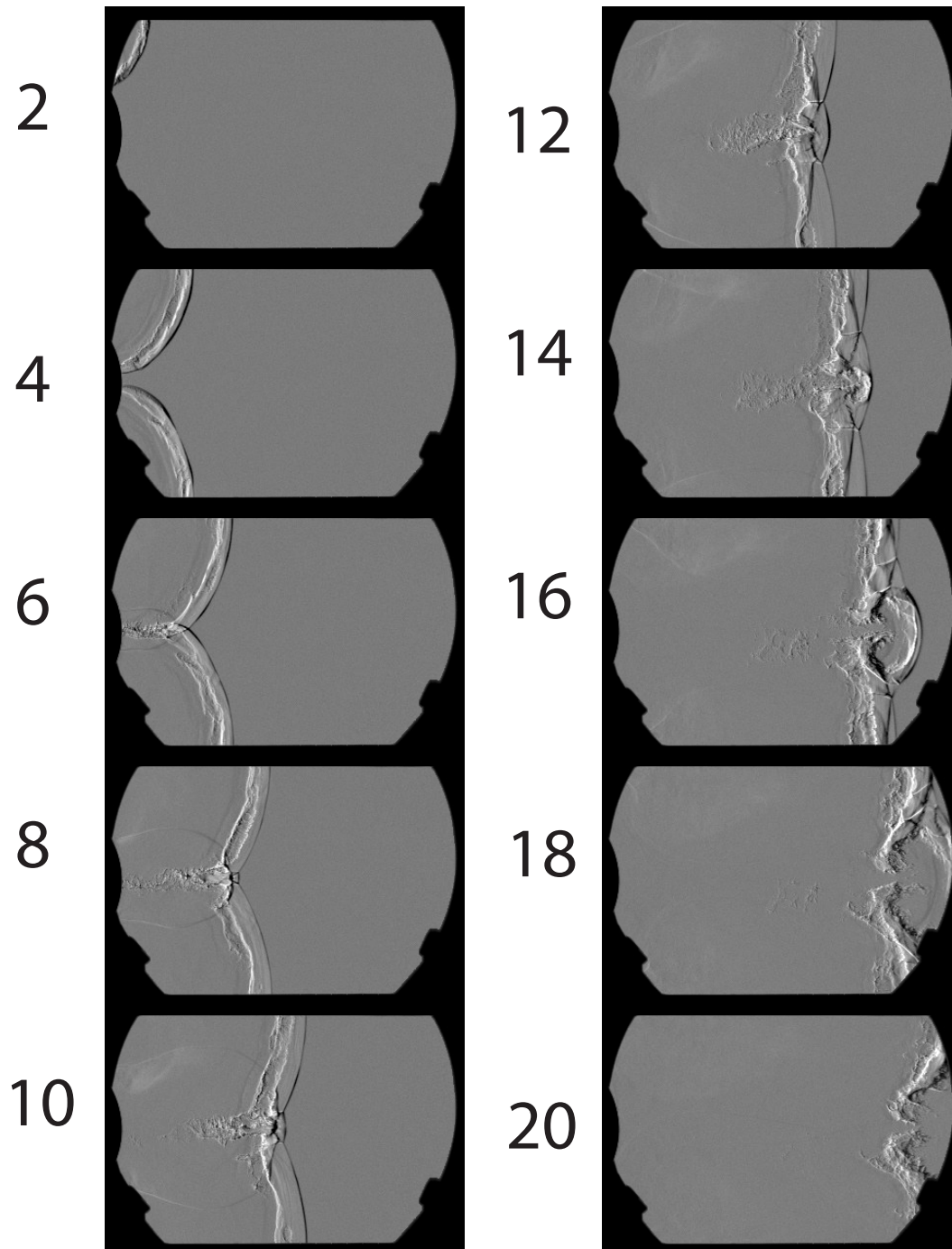


Figure 4.1: Schlieren record of methane-oxygen forward jet and reaction in jet, $p_0 = 8.3$ kPa. Recorded at $12.91 \mu\text{s}$ interframe time, $0.87 \mu\text{s}$ exposure, 77459.33 fps. The full experimental record can be found in Figure F.10.

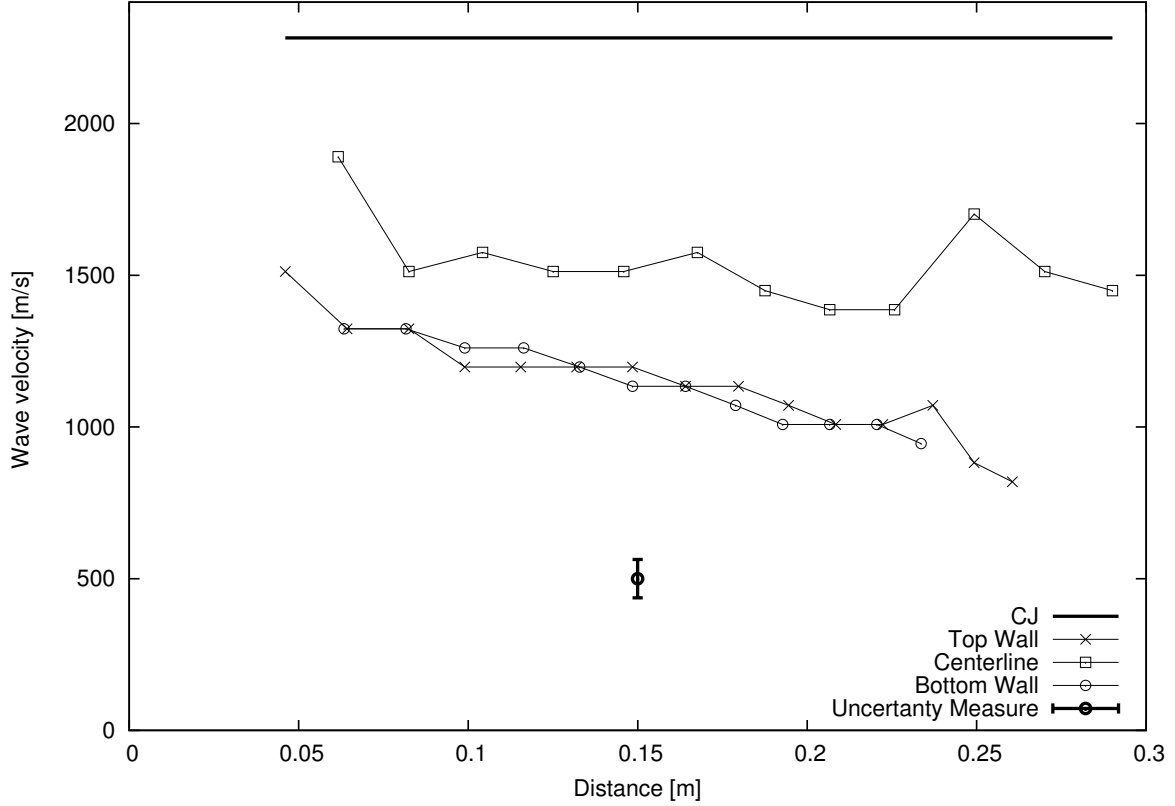


Figure 4.2: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 8.3$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

Repeating this experiment at a lower pressure, below the minimum sensitivity for a reactive reflection, we are able to observe the dominant hydrodynamics without the influences of the combustion in the region behind the reflection. Figure 4.3, $p_0 = 3.4$ kPa and $b/\lambda \simeq 0.39$ shows the un-reactive reflection in the wake of the cylinder. The first 10 frames of this experiment are almost identical to those seen above in the reactive case. The 12th frame allows the observation of the structure behind the Mach stem without the influences of the combustion. Here the slip lines meet behind the Mach stem and a forward jet can be seen. As the Mach stem expands, the coherent structures along the slip lines become more apparent, seen in frame 14. The region between the slip lines and behind the Mach stem appears to be a large vortical structure. This is below the lower pressure limit for reactive reflection. The velocity profile for this experiment shows a continuous decay in velocity, as seen in Figure 4.4.

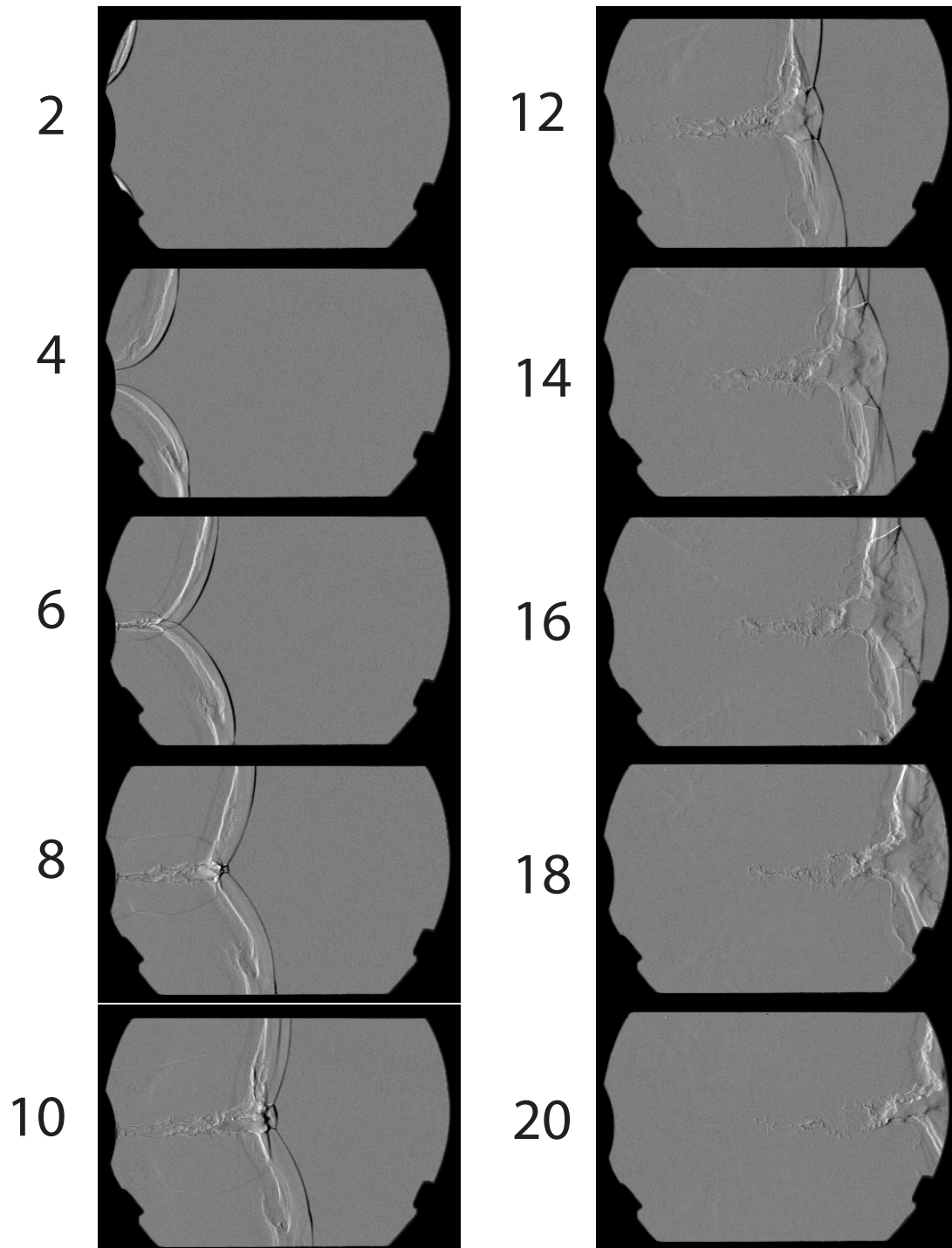


Figure 4.3: Schlieren record of methane-oxygen forward jet and non-reactive jet, $p_0 = 3.4$ kPa. Recorded at $12.91 \mu\text{s}$ interframe time, $0.87 \mu\text{s}$ exposure, 77459.33 fps. The full experimental record can be found in Figure F.11.

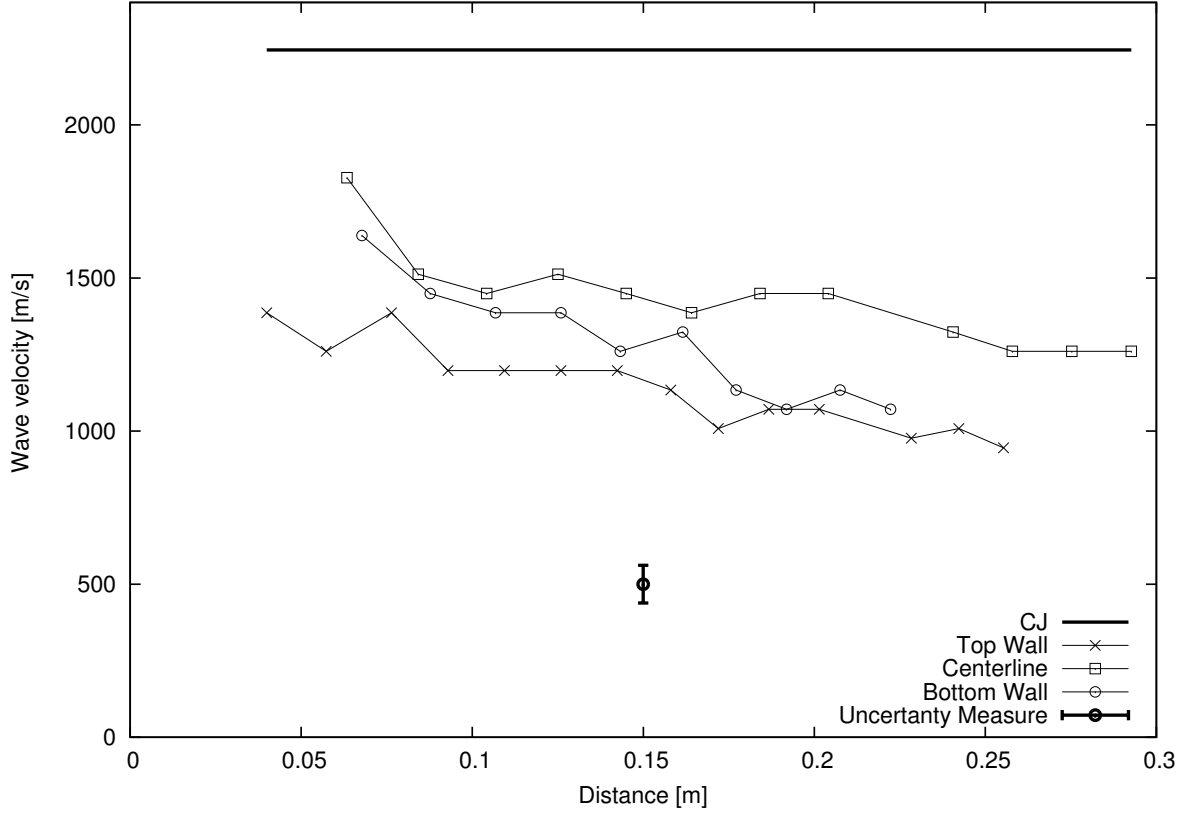


Figure 4.4: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 3.4$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

Further Downstream

Further downstream, using the Schlieren system, detonation transition was observed to happen suddenly, Figure 4.5 conducted with $p_0 = 8.4$ and $b/\lambda \simeq 0.75$. The remnants of a jet can be observed as the wave enters the field of view in frame 4. The jet and what seems to be a hot spot has engulfed the region behind the Mach stem. When this transverse wave reflects against the top wall, it has gained enough strength to initiate a detonation, as seen in frame 8. This detonation expands to fill the channel and displays the characteristic whisker-like structures caused by the transverse wave, indicative of an over-driven detonation. The velocity profile is seen in Figure 4.6. This shows the initiation of the detonation leading to an over-driven detonation which seems to decay towards the CJ velocity.

The most fundamental difference between the observations in hydrogen-oxygen and methane-oxygen is the continued reactive reflections observed in the methane-oxygen. We will focus upon the reflections to gain better insight into why there are more reactive reflections and thus a longer life span of the fast flame in methane-oxygen.

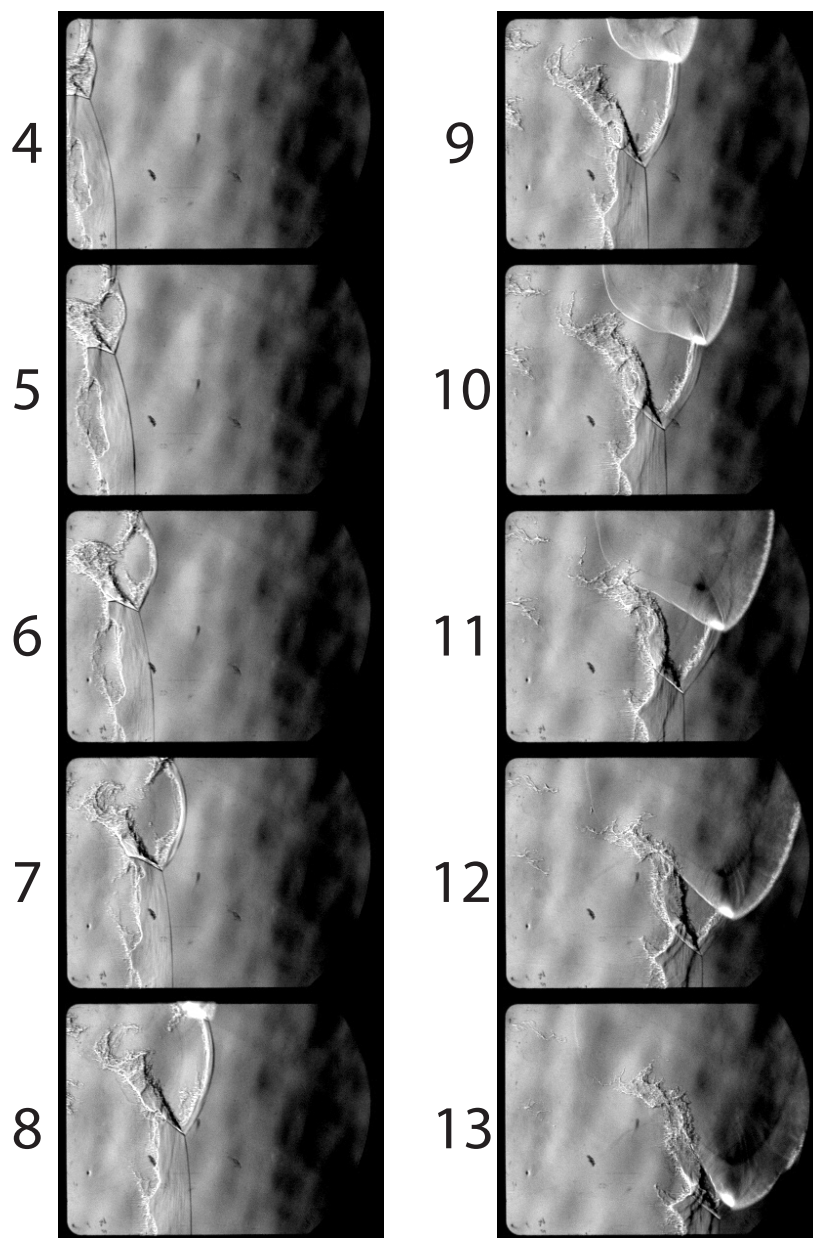


Figure 4.5: Schlieren record of methane-oxygen suddenly reflecting to form initiation of a detonation, $p_0 = 8.4$ kPa. Recorded at $12.91 \mu\text{s}$ interframe time, $0.87 \mu\text{s}$ exposure, 77101.00 fps. The full experimental record can be found in Figure F.12.

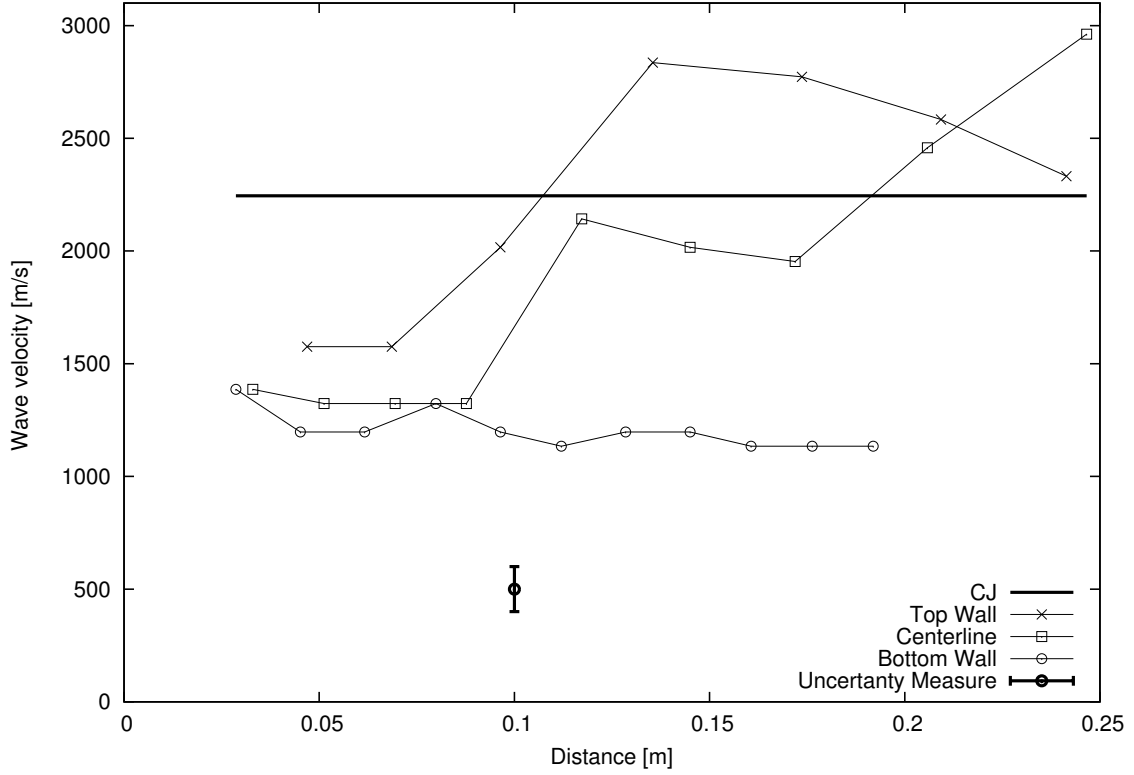


Figure 4.6: Velocity record from the above Schlieren images of methane-oxygen $p_0 = 8.4$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

4.1.2 Shadowgraph Records

Experiments conducted using a single cylinder obstacle were visualized with the shadowgraph system to gain a better understanding of the far field effects. In the case of the methane-oxygen, the highest pressure tested was $p_0 = 13.8$ kPa which corresponds to a sensitivity of $b/\lambda \simeq 1.44$, seen in Figures 4.7 & 4.8.

As the detonation diffracts around the cylinder in frame 2 of Figure 4.7 it is decoupled, as seen in frame 6. The transitional shock reflection in the wake of the cylinder in frame 8 initiates a detonation, expanding to fill the entire channel in frame 10. As the newly formed detonation propagates through the second half of the channel, Figure 4.8, it remains a detonation, displaying the characteristic wrinkled form indicative of a cellular detonation.

The velocity profile also shows that the wave decouples in the wake of the cylinder,

seen by the attenuation of the top and bottom wall velocities around $x = 0.2$. The Mach stem from the reflection immediately jumps to the CJ velocity, followed closely by the top and bottom wall velocities, to remain at the CJ velocity.

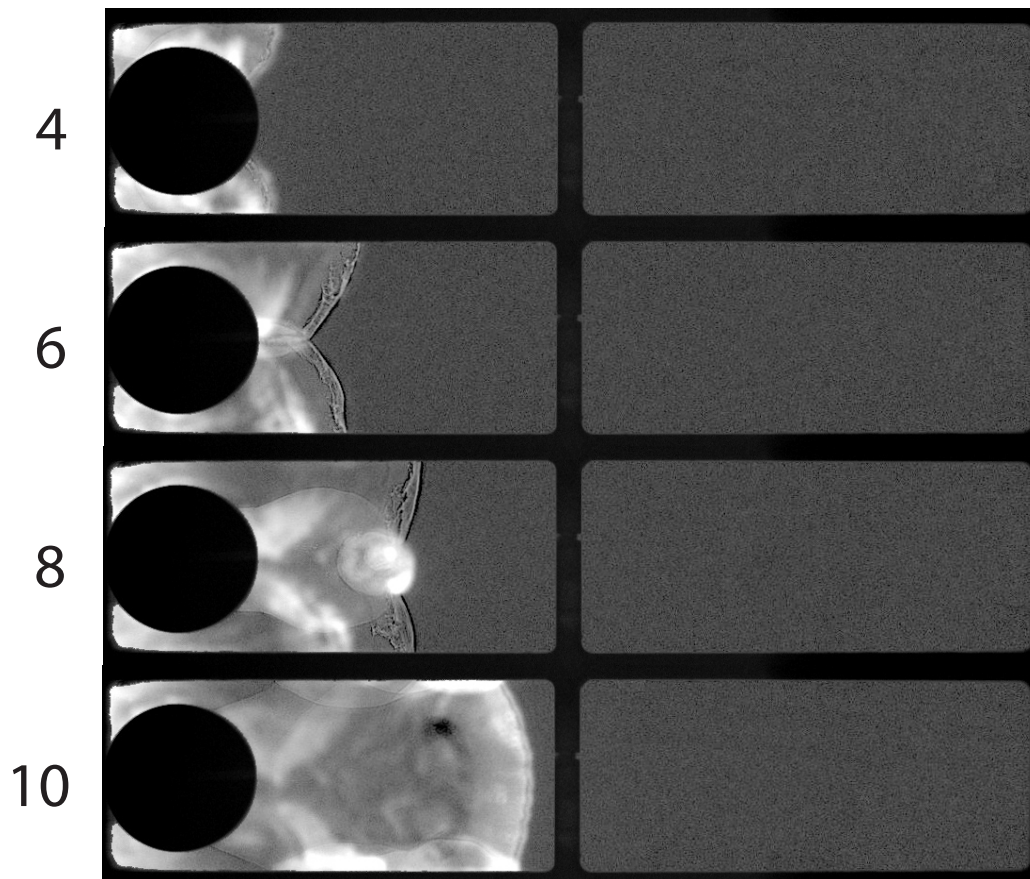


Figure 4.7: Shadowgraph record of methane-oxygen re-initiation following interaction with a single cylinder at $p_0 = 13.8$ kPa. Recorded at $25.63 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39016.7 fps. The full experimental record can be found at Figure F.13.

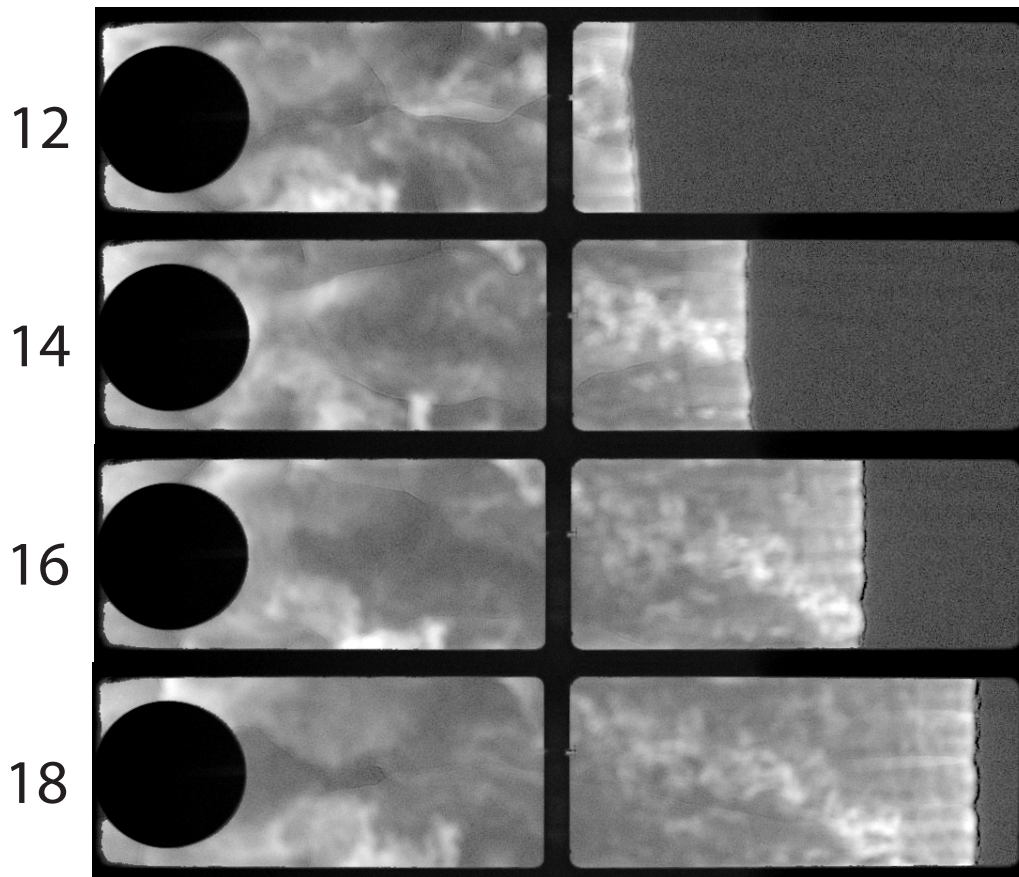


Figure 4.8: Shadowgraph record of methane-oxygen re-initiation following interaction with a single cylinder at $p_0 = 13.8$ kPa. Recorded at $25.63 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39016.7 fps. The full experimental record can be found at Figure F.13.

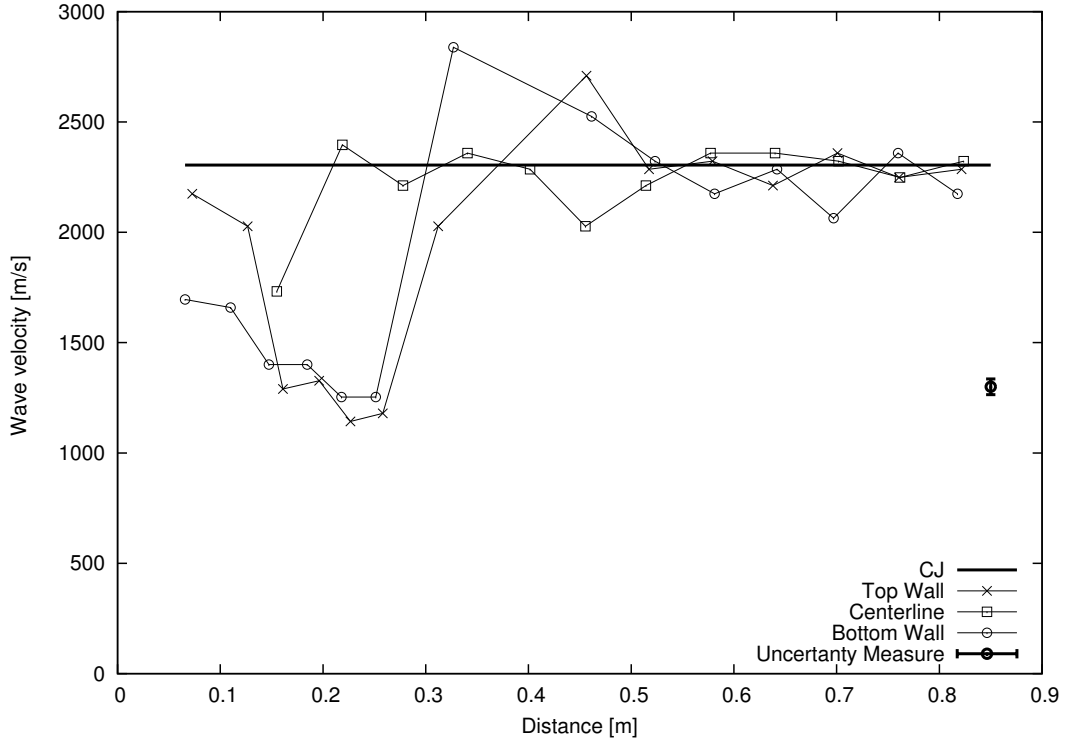


Figure 4.9: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 13.8$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

As the test pressure is lowered, the sensitivity of the gas is lowered, such that the first shock-shock reflection in the wake is unable to initiate a detonation. Figure 4.10 is an experimental Shadowgraph record of the formation of a hot spot, $p_0 = 11.0$ kPa and $b/\lambda \simeq 1.14$. As observed in the above experiments, when the first reflection is unable to initiate a detonation, it can form a reactive pocket or a hot spot, seen in frame 11.

Figure 4.11 shows that the hot spot produces transverse waves strong enough to initiate a detonation upon the first reflection with the wall, seen in frame 13. The two detonations meet in the center, propagating throughout the rest of the channel.

The velocity profile seen in Figure 4.12 shows a shock reflection which is unable to initiate a detonation along the center line. When the shock reflects off the top and bottom wall, the velocity jump above the CJ velocity and the wave continues at approximately the CJ velocity for the rest of the channel.

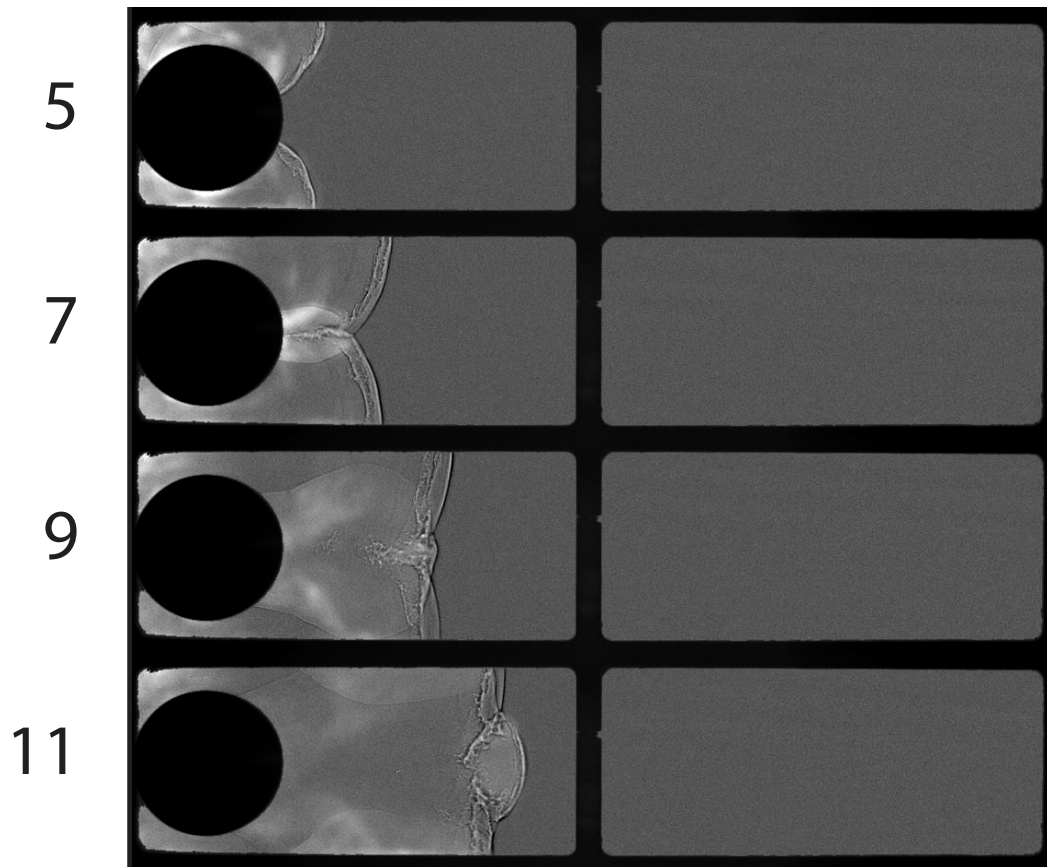


Figure 4.10: Shadowgraph record of methane-oxygen detonation initiation upon second reflection, $p_0 = 11.00$ kPa. Recorded at $25.63 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39016.7 fps. The full experimental record can be found in Figure F.14.

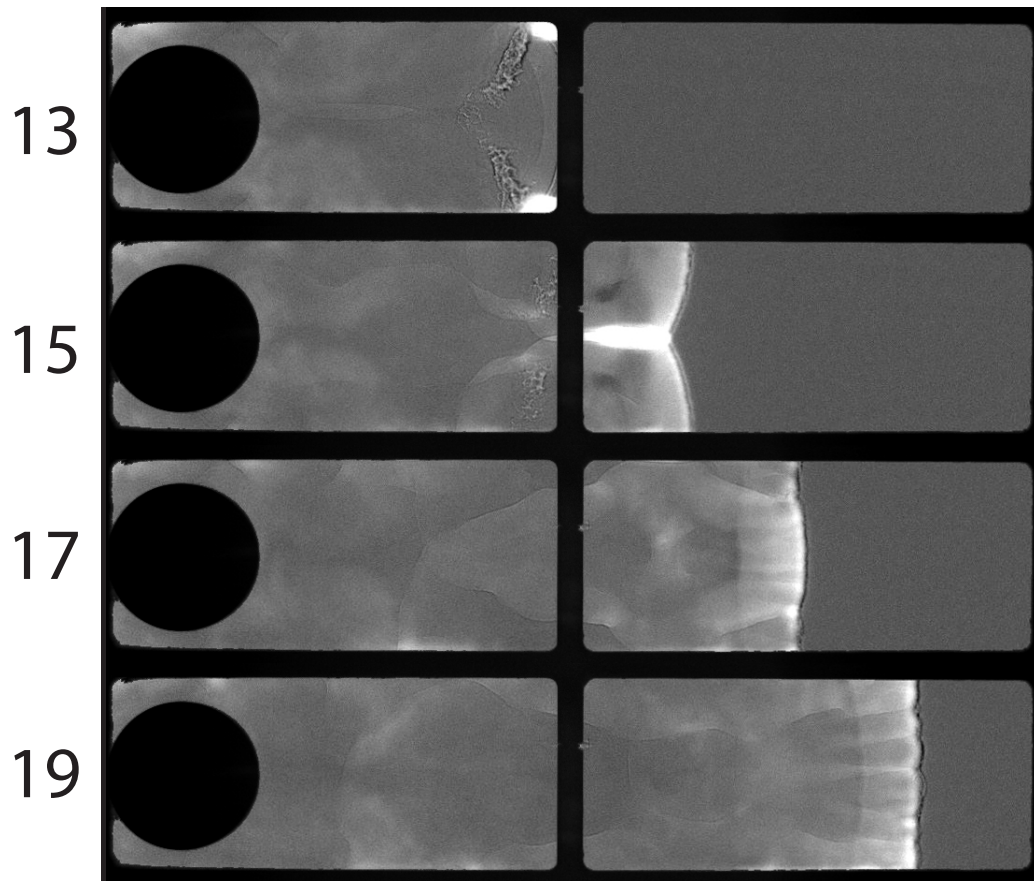


Figure 4.11: Shadowgraph record of methane-oxygen detonation initiation upon second reflection, $p_0 = 11.00$ kPa. Recorded at $25.63 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39016.7 fps. The full experimental record can be found in Figure F.14.

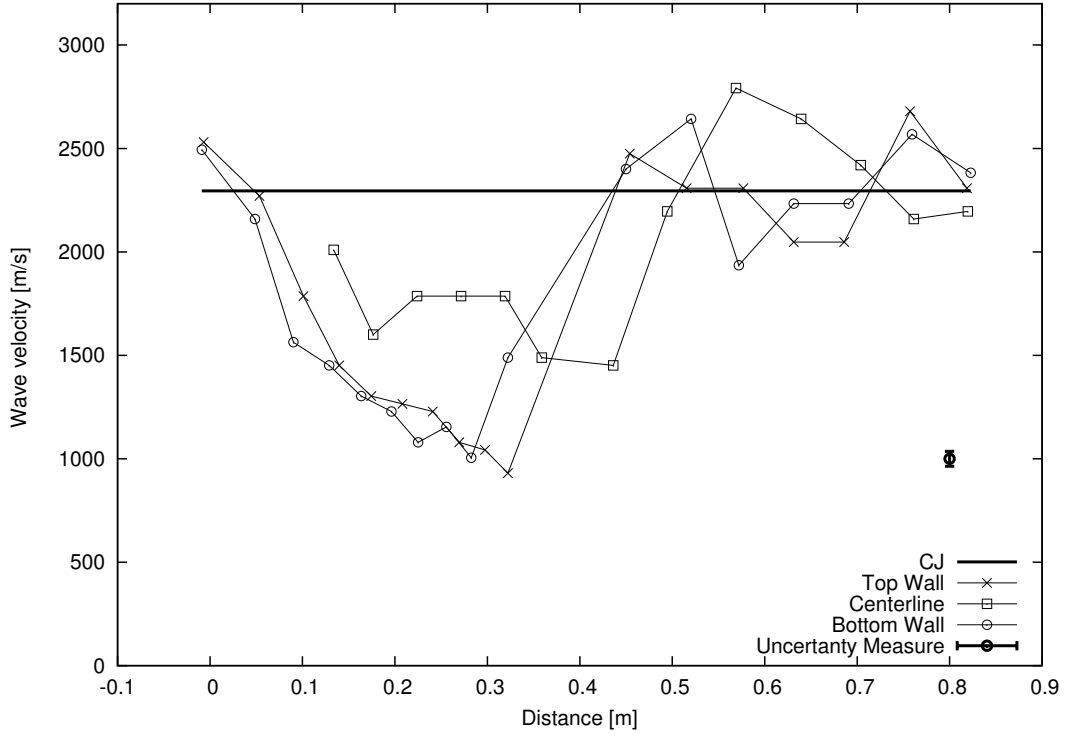


Figure 4.12: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 11.0$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

When the pressure is further lowered, $p_0 = 9.6$ kPa corresponding to $b/\lambda \simeq 0.93$, Figures 4.13 & 4.14 show the detonation initiation further delayed until the 4th shock reflection. As the wave enters from the left, the detonation fails around the cylinder, frame 4. Then the first shock-shock reflection ignites a hot spot and expands with the transverse pressure waves, frame 10. The second reflection is a shock-wall reflection. In this case the asymmetry produces a stronger reflection with the top wall, evident by the burst of self-luminosity in frame 12.

Figure 4.14 shows the larger hot spot caused by this reflection with the top wall expanding down to overtake the rest of the wave. Frame 18 is taken just after the asymmetrical shock-shock reflection. Upon reflection with the bottom wall the reflection has gained enough strength to initiate a detonation, seen expanding in frame 22.

The velocity profile in Figure 4.15 shows how the velocity oscillates with each series of reflections. The shock reflection in the center of the channel is seen at approximately $x = 0.15$ m. This leads to two slightly asymmetrical shock reflections with the top and

bottom walls at approximately $x = 0.3$ m. These two shock reflections then lead to a jump in the centreline velocity at $x = 0.55$ m. Near the end of the channel the bottom wall velocity jumps above the CJ velocity, confirming the initiation of a detonation.

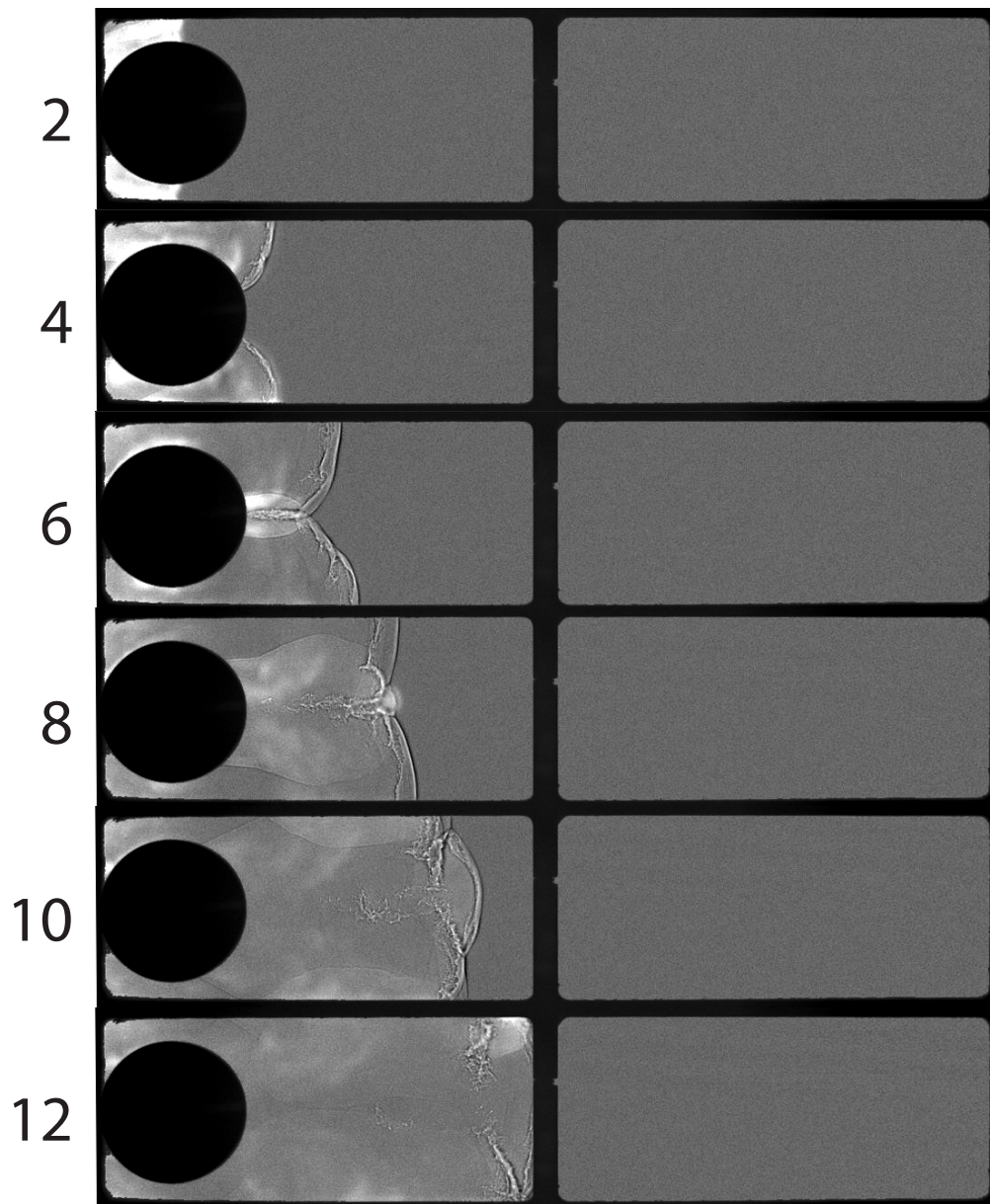


Figure 4.13: Shadowgraph record of methane-oxygen detonation initiation upon fourth reflection, $p_0 = 9.6$ kPa. Recorded at $25.62 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39032.0 fps. The full experimental record can be found in Figure F.15.

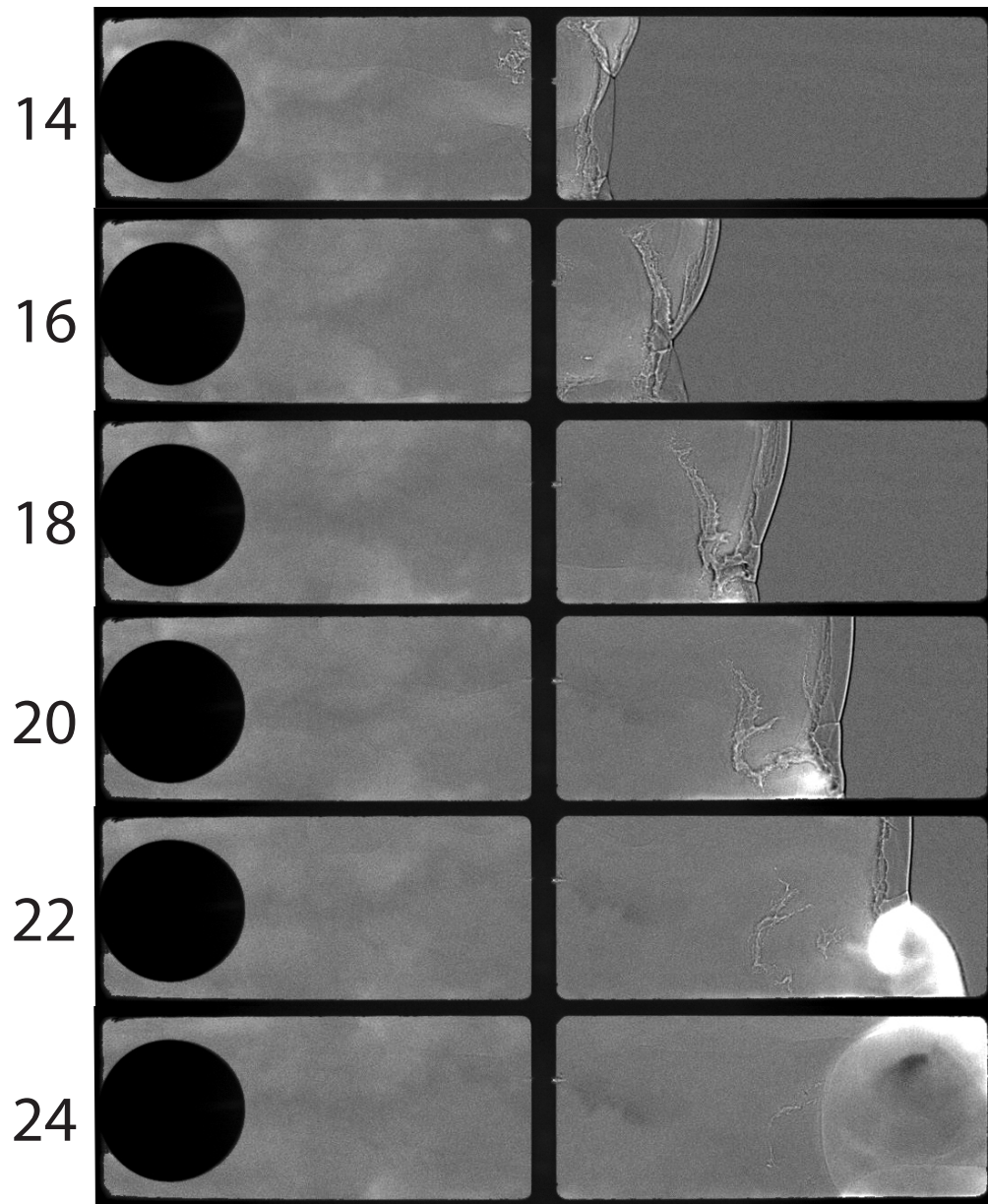


Figure 4.14: Shadowgraph record of methane-oxygen detonation initiation upon fourth reflection, $p_0 = 9.6$ kPa. Recorded at $25.62 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39032.0 fps. The full experimental record can be found in Figure F.15.

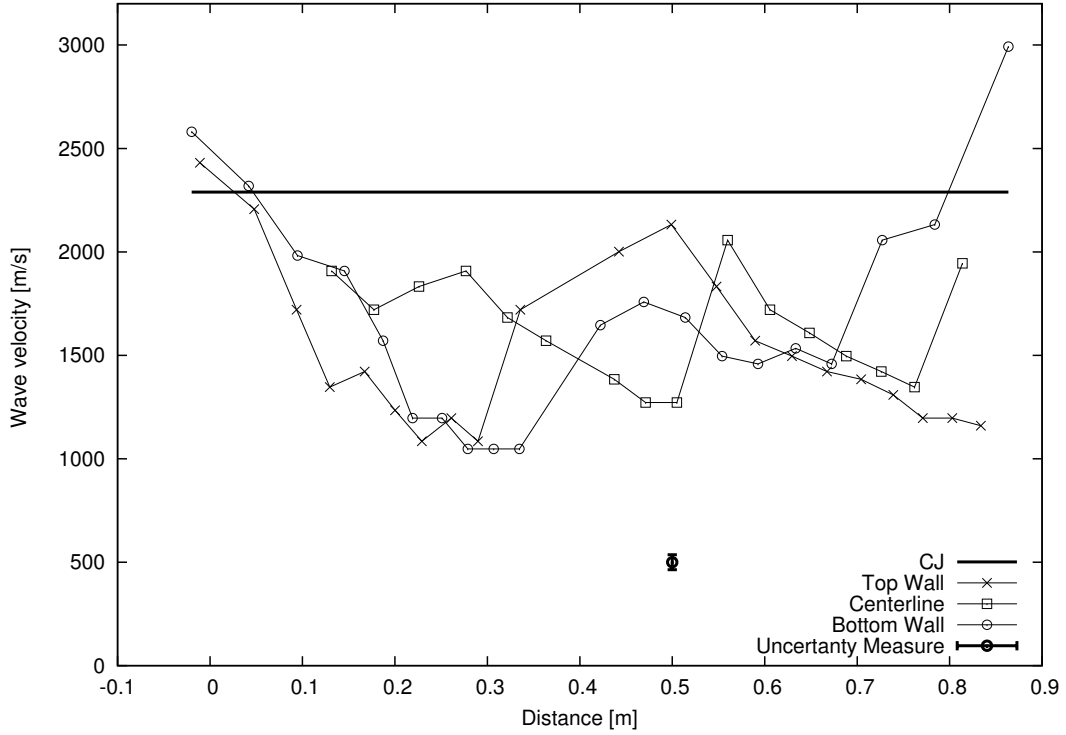


Figure 4.15: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 9.6$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

Again, lowering the pressure leads to the fast flame enduring for a longer distance. Figure 4.16 is the shadowgraph record of an experiment conducted at $p_0 = 8.5$ kPa and $b/\lambda \simeq 0.78$. The initial development of the fast flame has become a familiar series of events; however, this symmetrical experiment differs as the shock-shock reflection, beginning in frame 17, shows good insight into the physical structures underlying the combustion.

Upon reflection in the center of the channel, a prominent jet structure is clearly visible beginning in frame 19 and developing into frame 21. Frame 23 of Figure 4.17 shows the beginning of flame acceleration into the jet structure. This acceleration further develops in frame 25 when the pocket of reactive gas quickly engulfs the region behind the Mach stem.

The velocity profile of the lead shock, seen in Figure 4.18, shows the velocity jumps as described above. Each reflection gives rise to a jump in the velocity. These oscillations remain under the CJ velocity throughout the length of the channel.

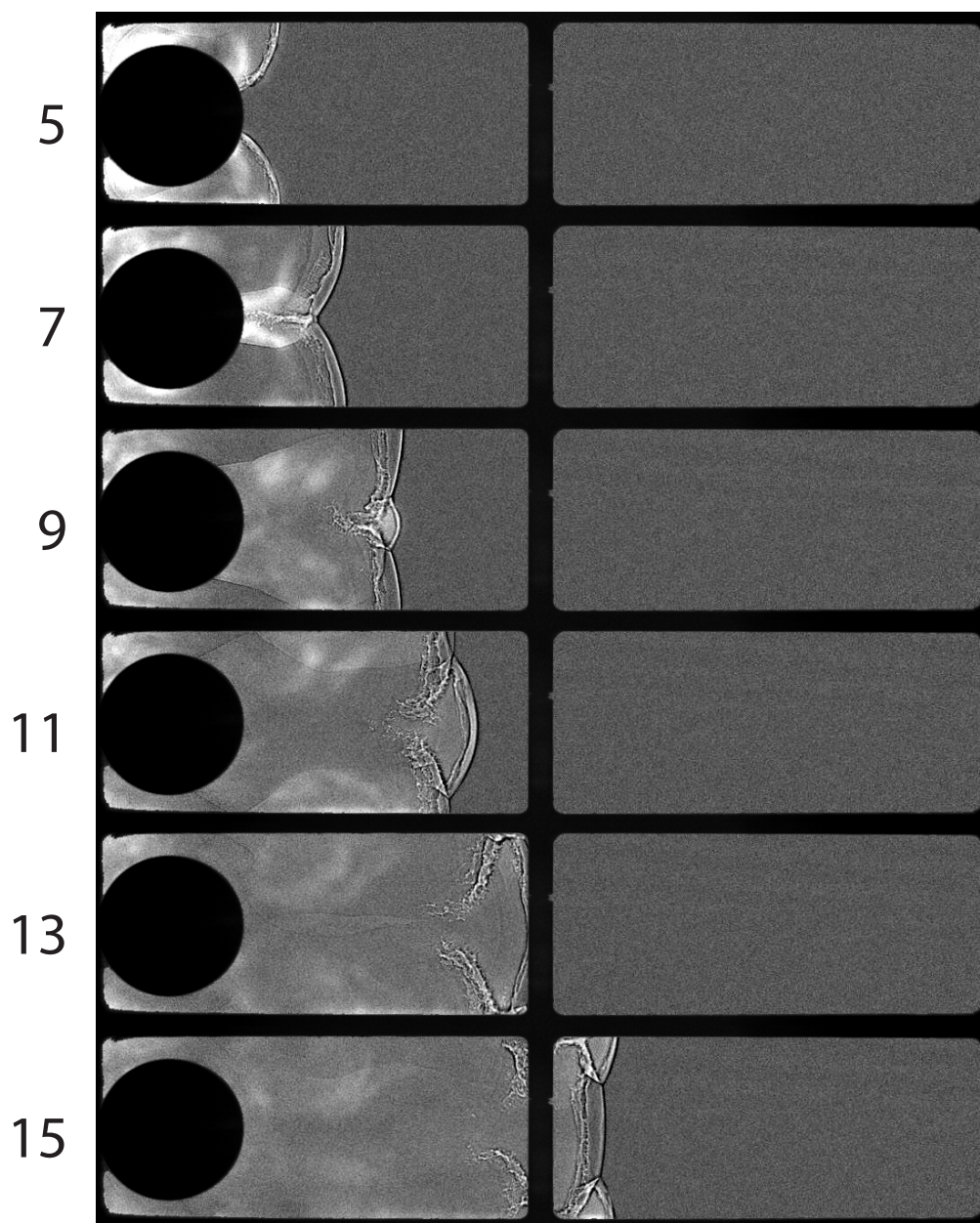


Figure 4.16: Shadowgraph record of methane-oxygen forward jet and delayed reaction in jet, $p_0 = 8.5$ kPa. Recorded at $25.63 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39016.7 fps. The full experimental record can be found in Figure F.16.

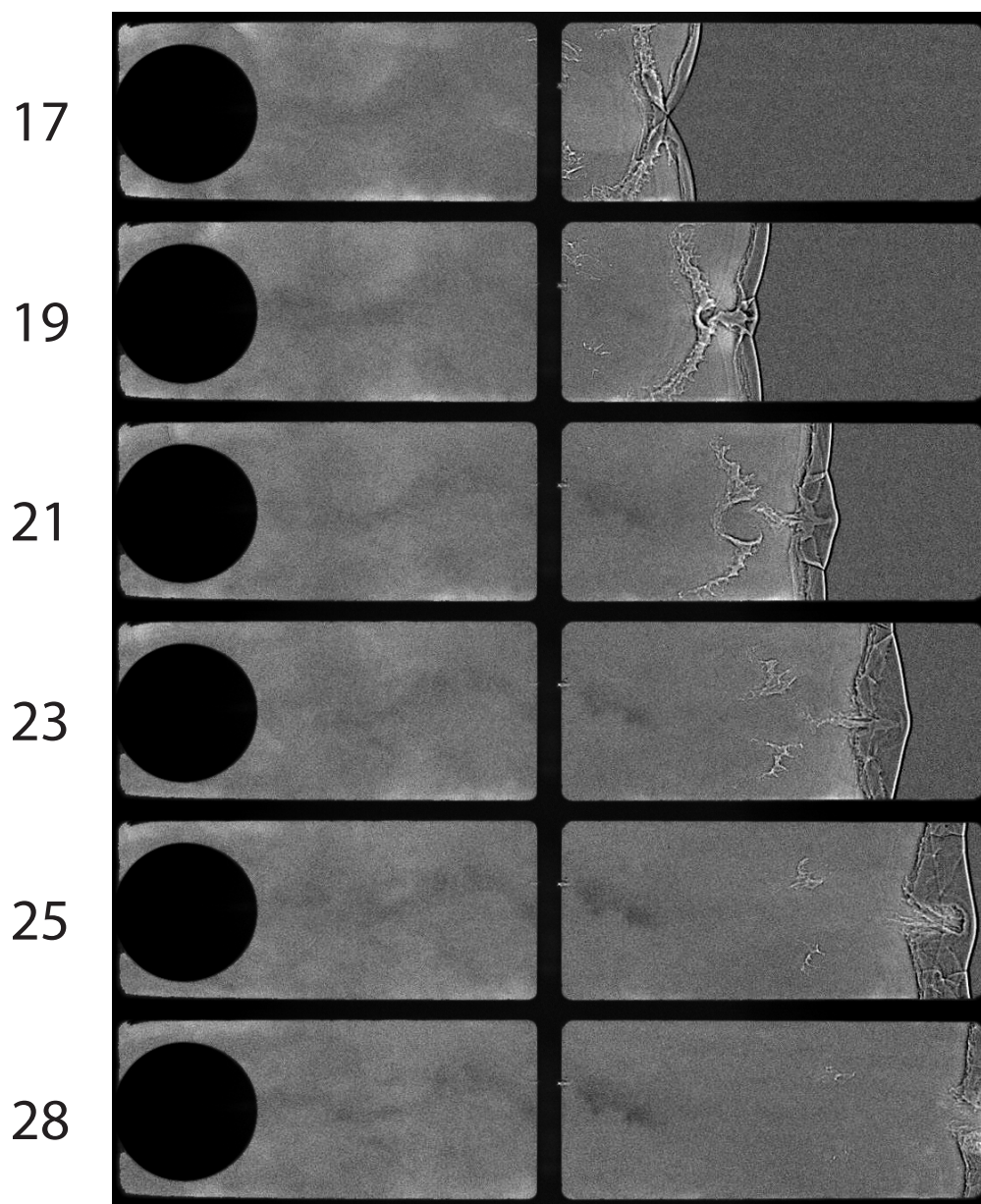


Figure 4.17: Shadowgraph record of methane-oxygen forward jet and delayed reaction in jet, $p_0 = 8.5$ kPa. Recorded at $25.63 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39016.7 fps. The full experimental record can be found in Figure F.16.

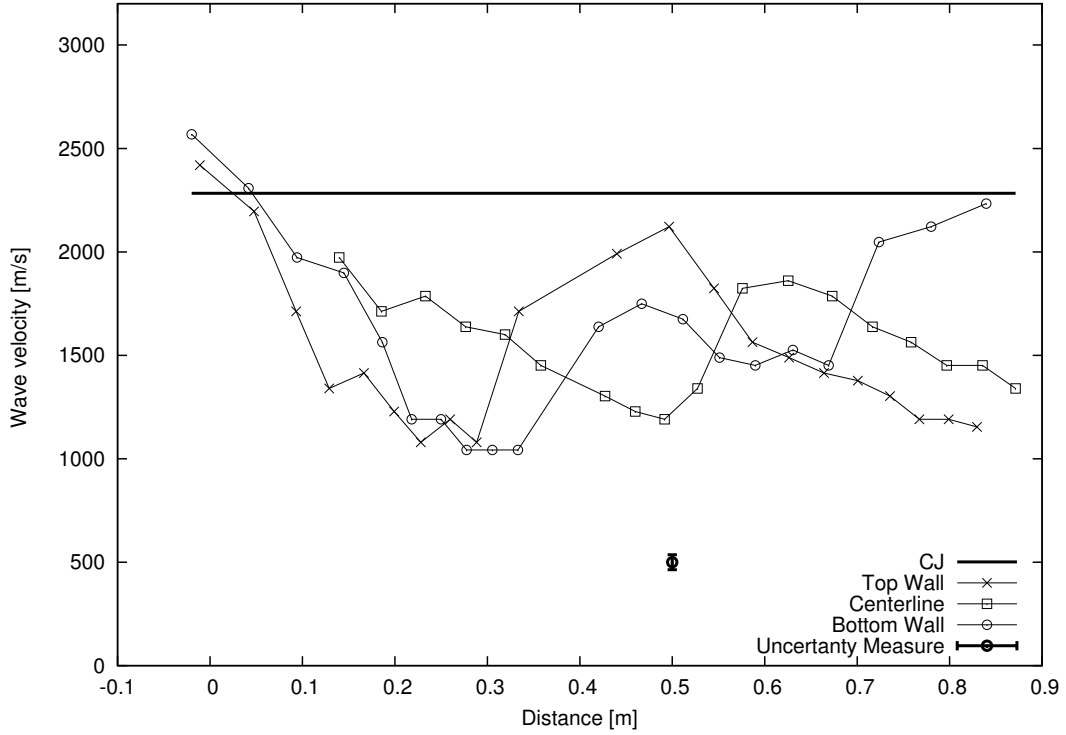


Figure 4.18: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 8.5$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

4.1.3 Self-Luminous Records

In an attempt to gain a different perspective on this phenomenon, self-luminous experiments were conducted. As described above, these experiments were conducted in the channel with the single cylinder obstacle and directly visualized with the high speed camera.

This experiment was conducted at an initial pressure of $p_0 = 8.4$ kPa and $b/\lambda \simeq 0.75$. This series of photographs, Figure 4.19-4.22, were taken using a $1 \mu\text{s}$ exposure, and an interframe time of $57.1 \mu\text{s}$. The reactive keystone structures caused by the shock reflections are seen in frames 29 of Figure 4.20 and frame 49 of 4.21. Figure 4.22 Frame 85 shows a reacted pocket of gas in the center of the channel, expanding into frame 93. This resembles the jet structure observed in Figure 4.17

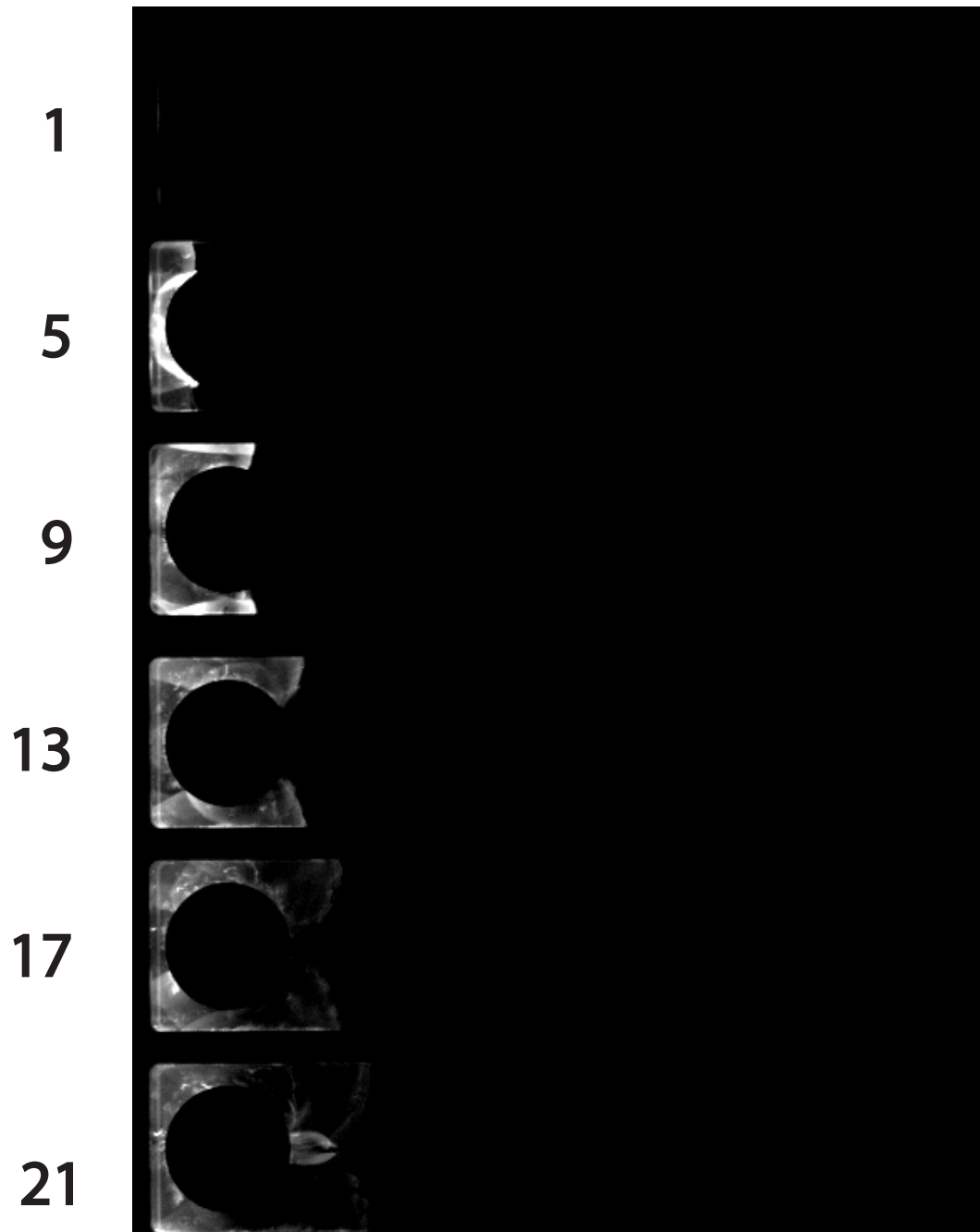


Figure 4.19: Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa. Full experimental record can be found in Figure F.17,F.18, F.19 & F.20.

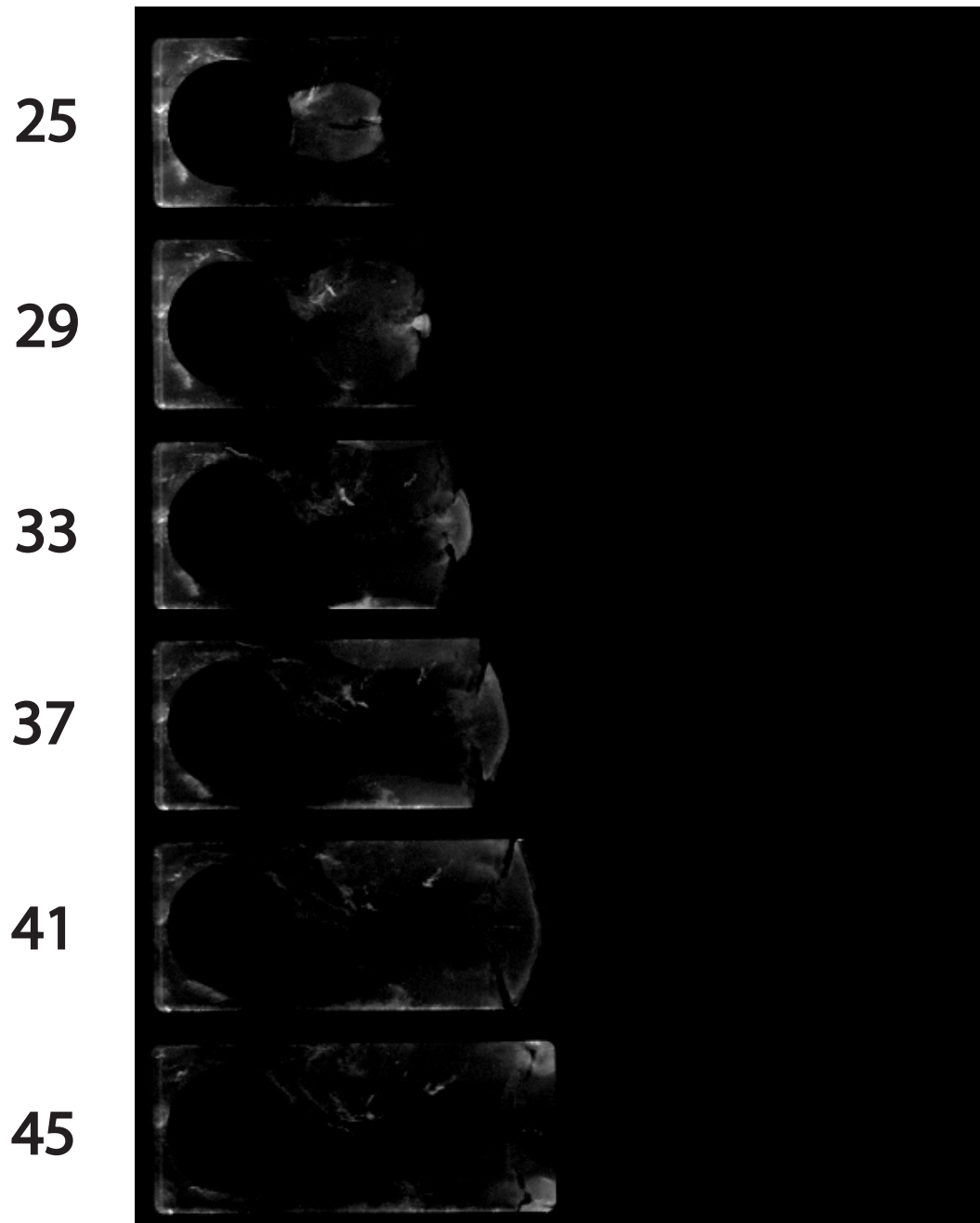


Figure 4.20: Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa. Full experimental record can be found in Figure F.17, F.18, F.19 & F.20.

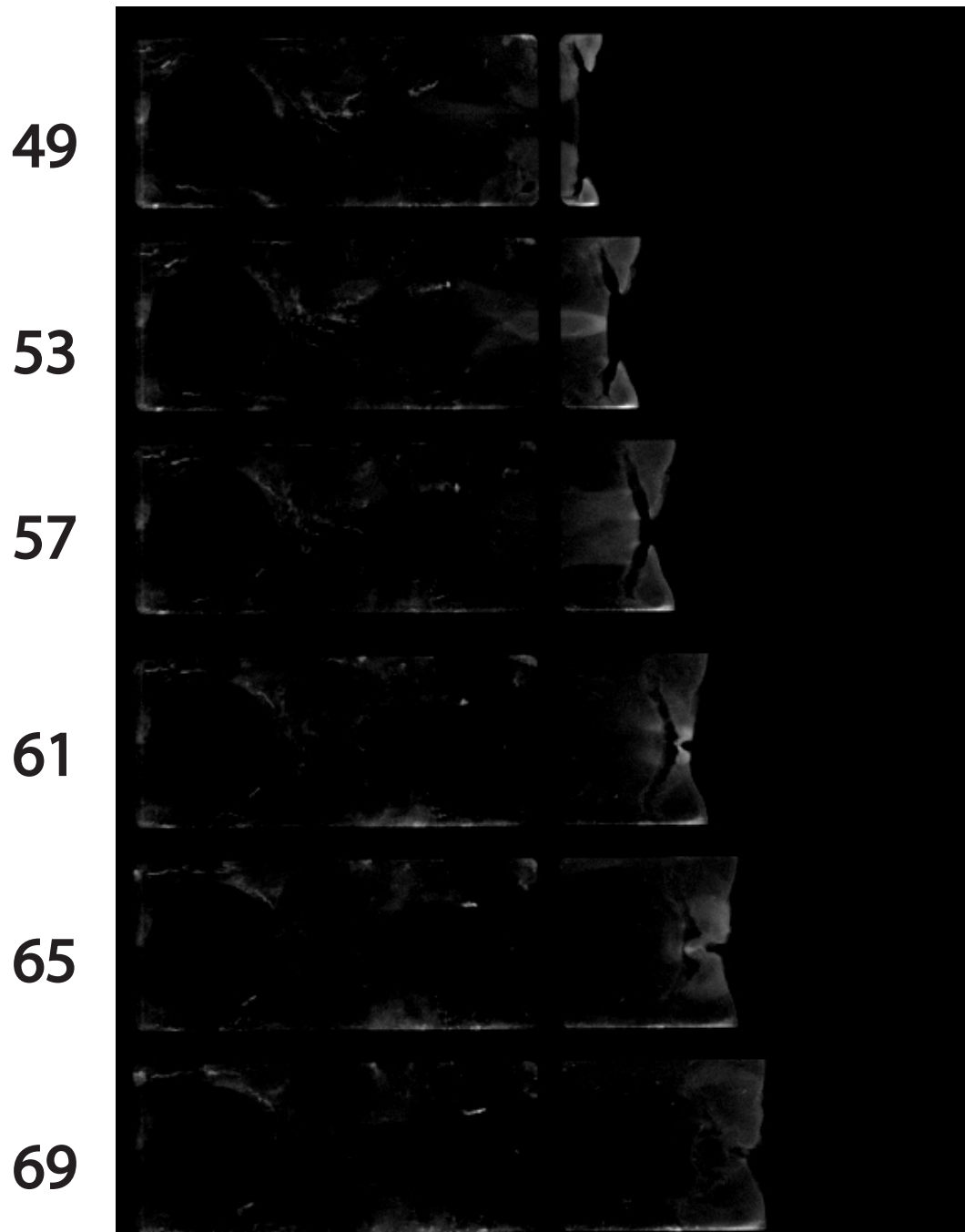


Figure 4.21: Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa. Full experimental record can be found in Figure F.17, F.18, F.19 & F.20.

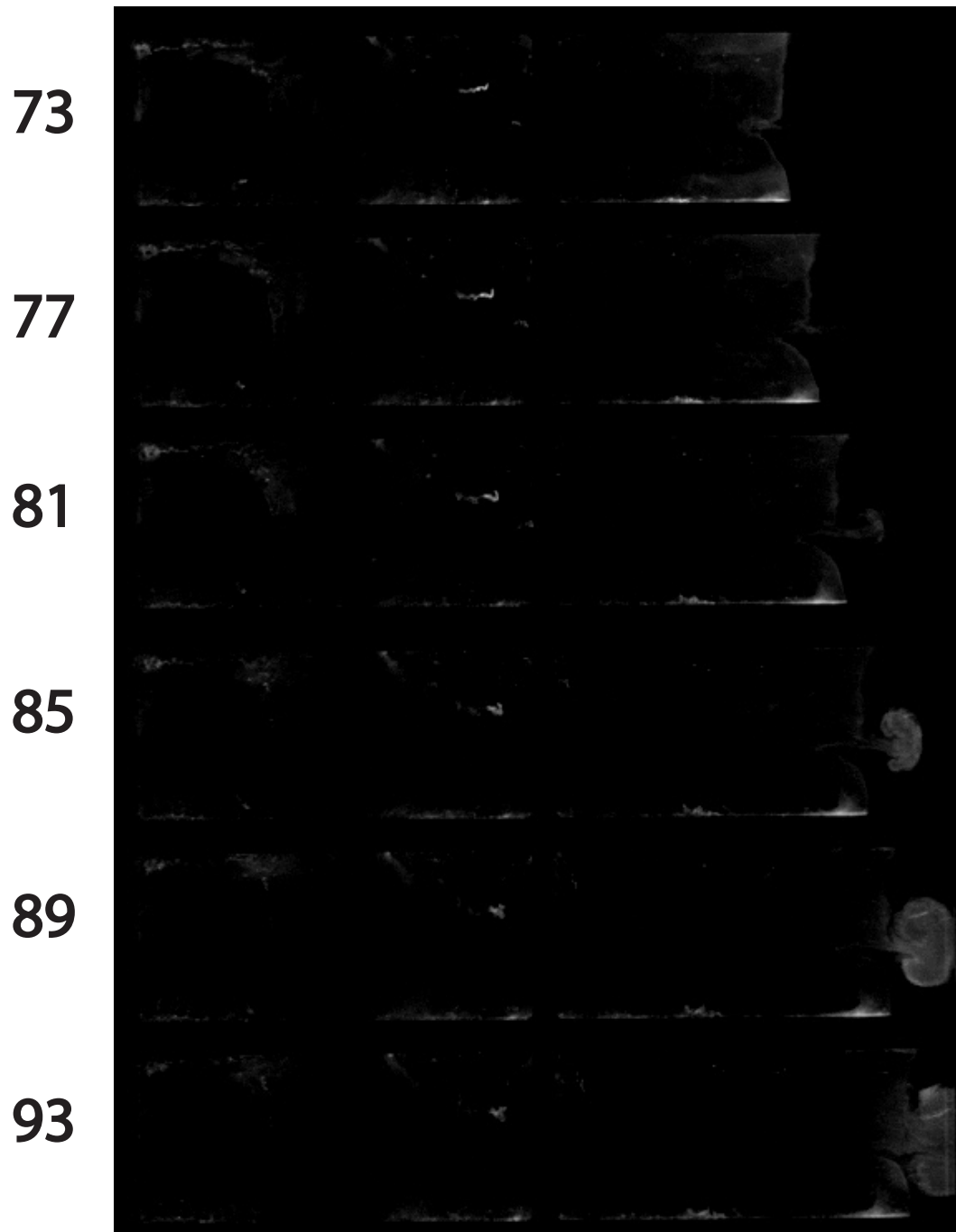


Figure 4.22: Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 8.5$ kPa. Full experimental record can be found in Figure F.17, F.18, F.19 & F.20.

Figure 4.23 was conducted at $p_0 = 6.9$ kPa and $b/\lambda \simeq 0.59$. This experiment shows the detonation initiation along the bottom wall. Figure 4.25, $p_0 = 6.9$ kPa and $b/\lambda \simeq 0.59$

shows the section of the experiment where the shock-wall reflection initiates a detonation.

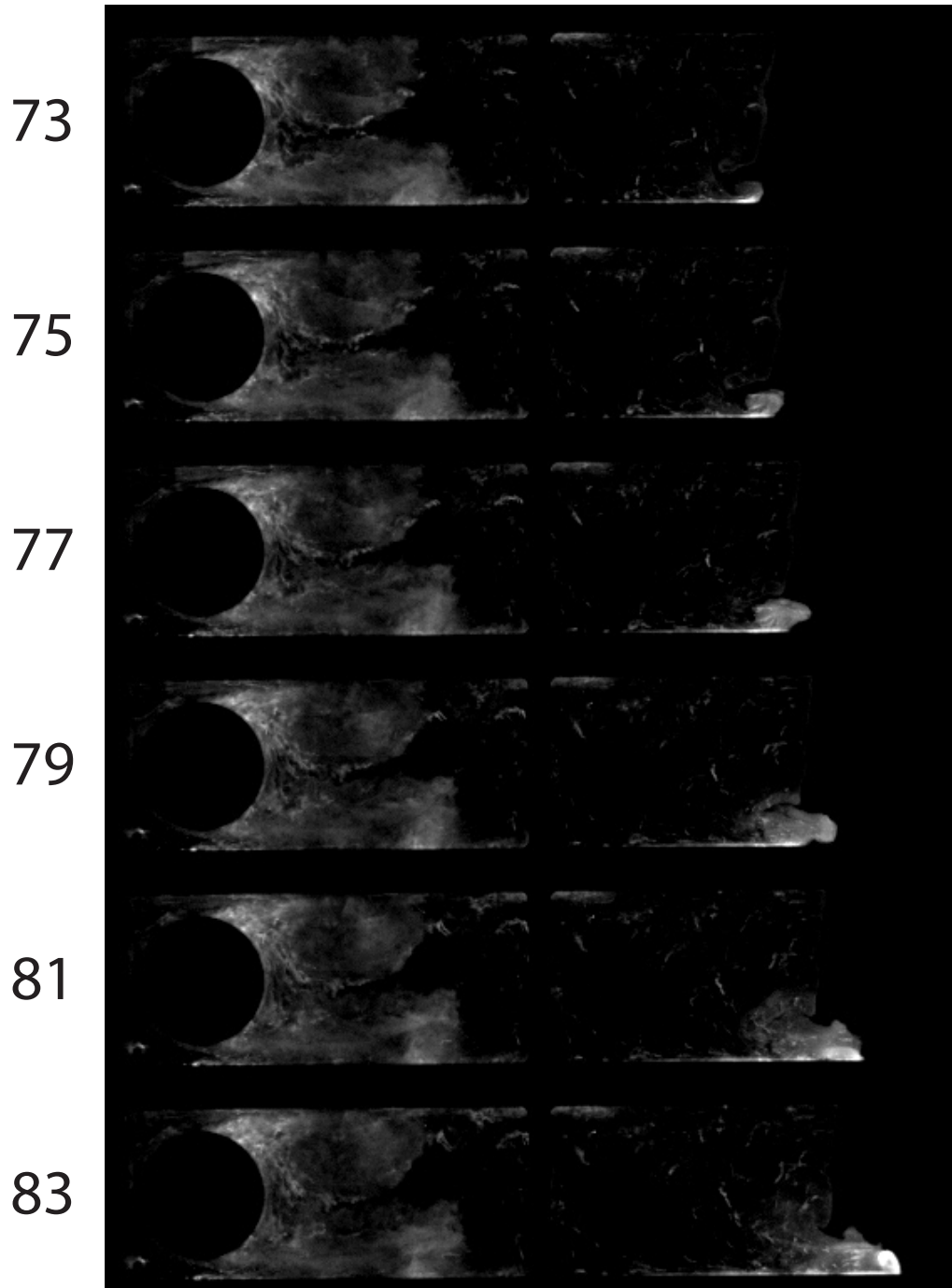


Figure 4.23: Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 6.9$ kPa. Full experimental record can be found in Figure F.21, F.22, F.23, & F.24.

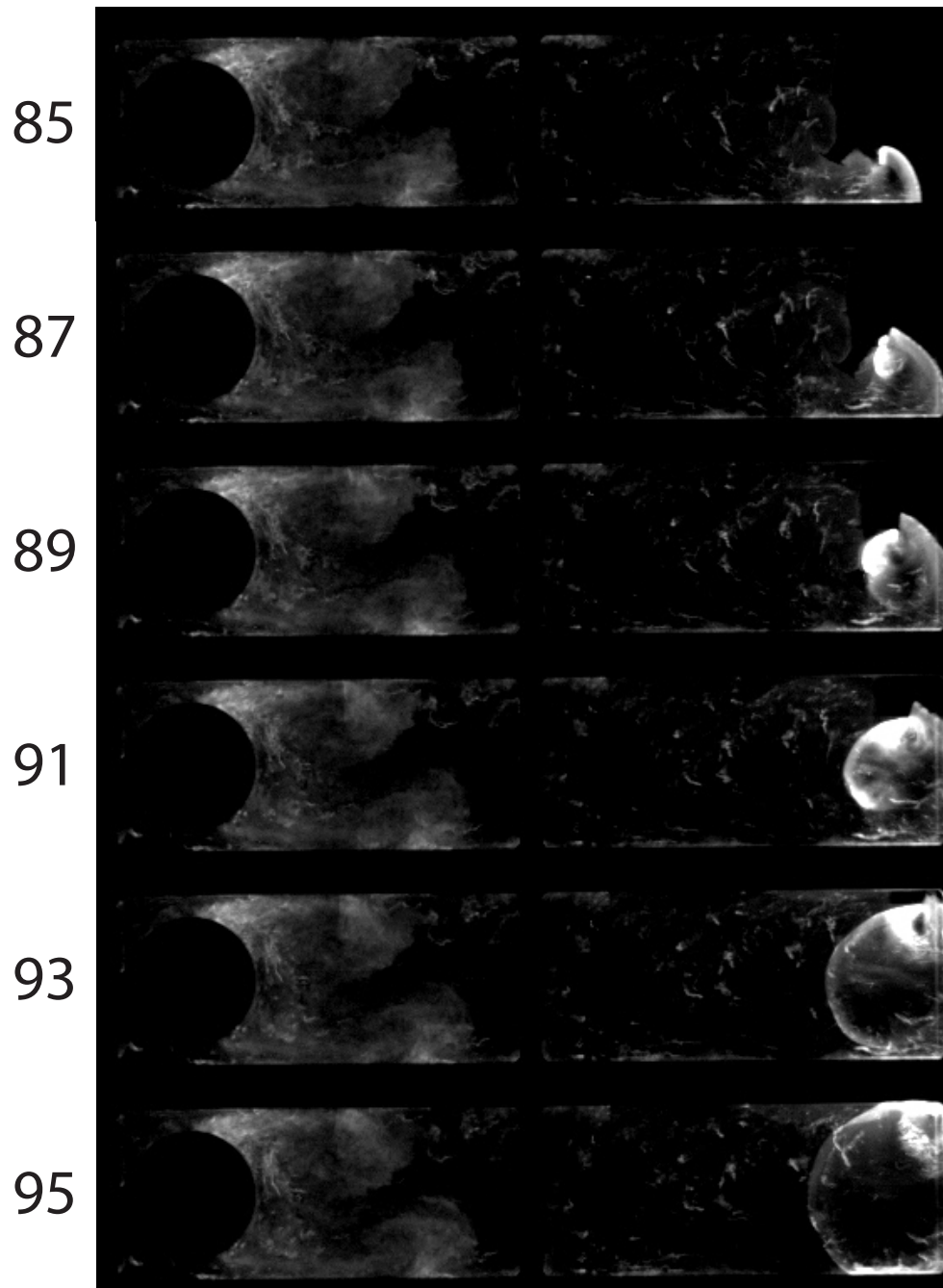


Figure 4.24: Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 6.9$ kPa. Full experimental record can be found in Figure F.21, F.22, F.23, & F.24.

Figure 4.25 shows the center jet is observed but no detonation initiation is seen in the channel. Frame 62 shows the beginning of a hot spot formed in the center of the

channel. This structure again resembling that seen in Figure 4.17. In this case no detonation initiation was observed.

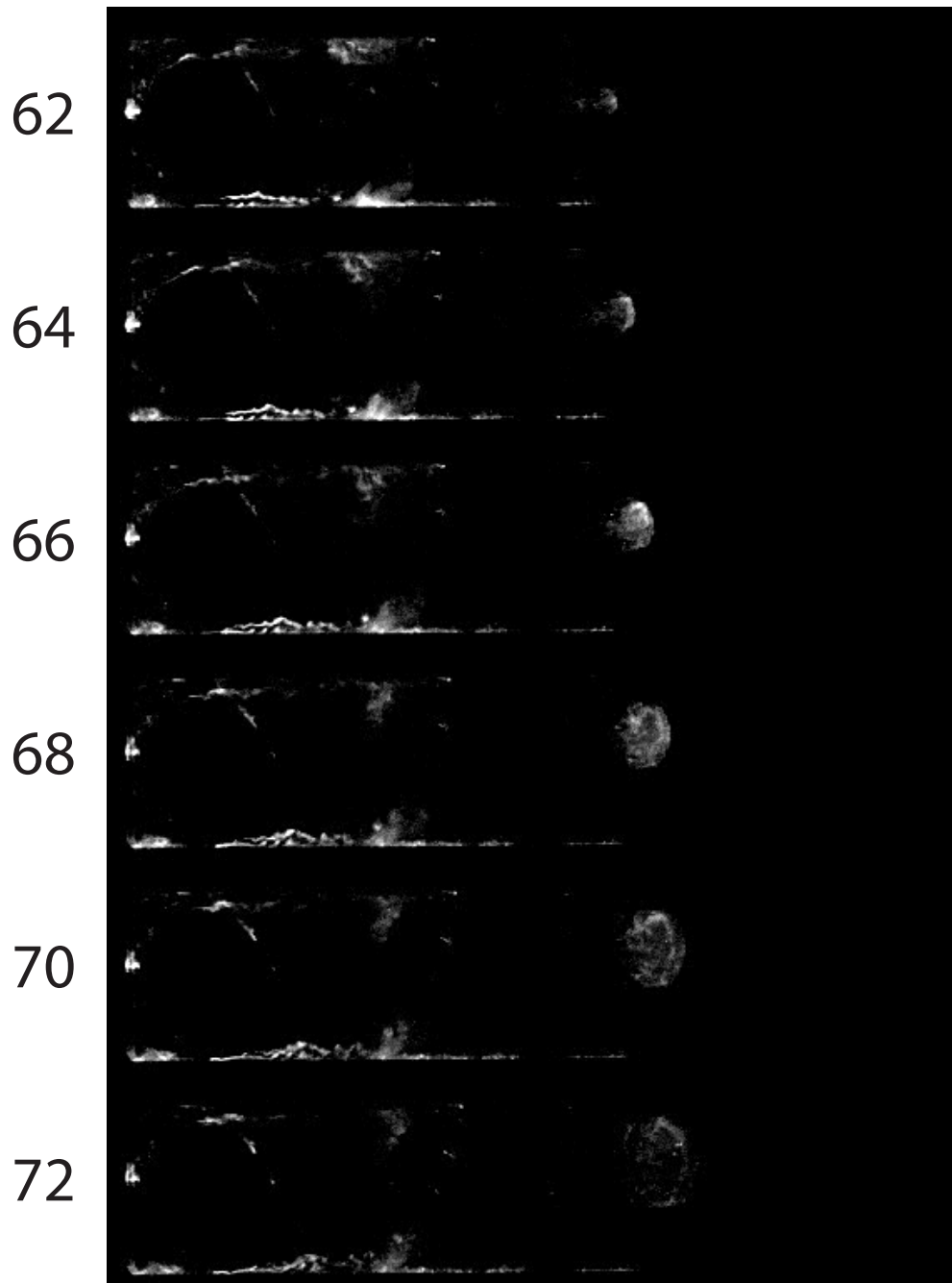


Figure 4.25: Direct visualization record of the self-luminosity in methane-oxygen at $p_0 = 6.9$ kPa. Full experimental record can be found in Figure F.25, F.26, F.27, F.28, & F.2.3.

4.2 Five Obstacle Experiments

4.2.1 Schlieren Records

The highest pressure tested with the five obstacles, $p_0 = 17.9$ kPa visualized using the Schlieren optical system, Figure 4.26 corresponds to a sensitivity of $b/\lambda \simeq 0.37$. This record shows the initial detonation entering from the left, frame 2, and interacting with the obstacles, frame 4. Frame 5 shows the characteristic shock diffraction pattern previously seen, decoupling the shock and reaction zone. The translational Mach reflection as seen in frame 6 gives rise to the growth of hotspots in frame 7. As these hot spots grow in frames 8 and 9 the transverse waves reflect and form a second generation of hotspots in frame 10.

The slight asymmetries in the initial detonation become apparent again in the second generation of hotspots in Figure 4.27. As these hotspots grow, the asymmetrical shock reflections produce an asymmetrical wave structure, frame 11. This leads to another generation of shock reflections of varying strengths. Frame 12 shows a hot spot in the center of the frame. As this hot spot expands in frame 12, the expansion further decouples the reaction zone, but this shock wave leads to a reflection in the center of the frame, frame 13. This reflection produces a detonation initiation visible in frame 14. The transverse waves are distinctive of a detonation. Frame 15 also shows the whisker-like transverse waves trailing the wave which is characteristic of an over-driven detonation.

The velocity profile, Figure 4.28 shows an attenuation of the initial detonation. The velocity oscillates along the channel, followed by a jump in the centreline velocity of cylinder 2 and 3 above the CJ velocity.

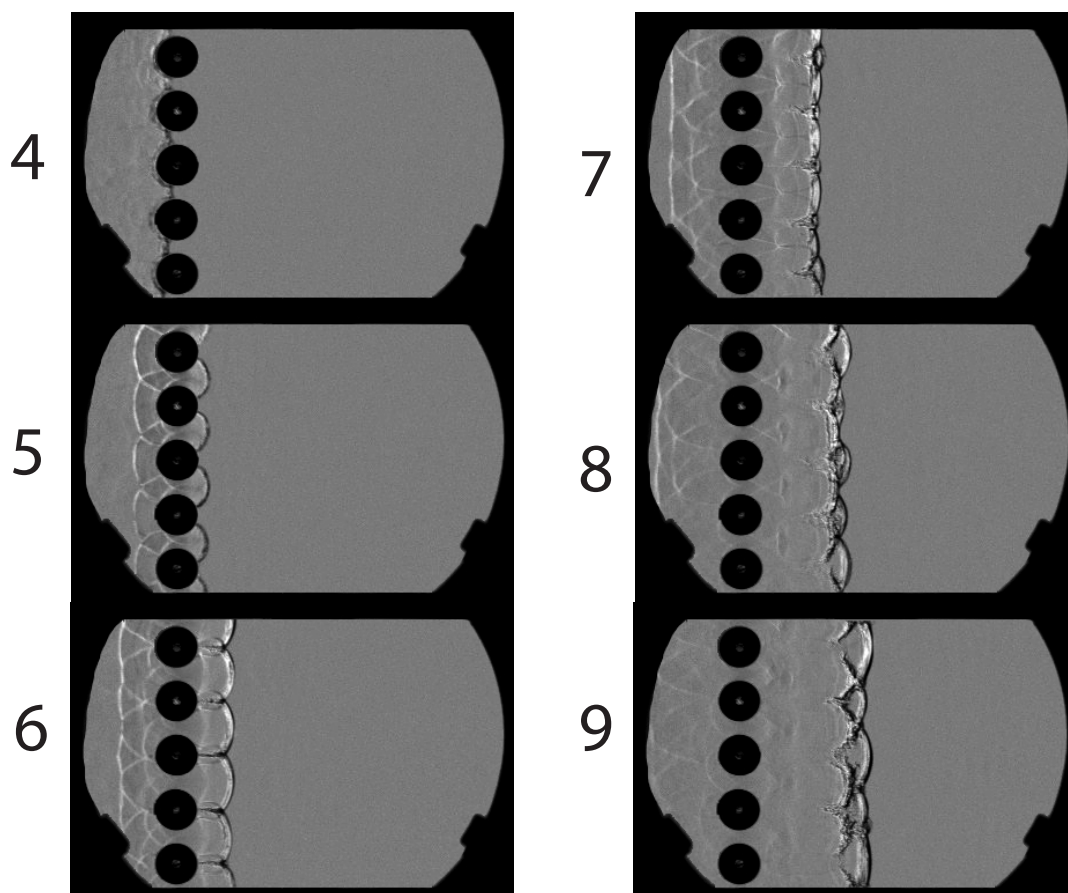


Figure 4.26: Shadowgraph images illustrating the decay of the fast flame in CH_4+2O_2 $p_0 = 17.9$ kPa. Recorded at $11.62 \mu\text{s}$ interframe time, $0.91 \mu\text{s}$ exposure, 86058.51 fps, the full experimental record can be found in Figure F.1.

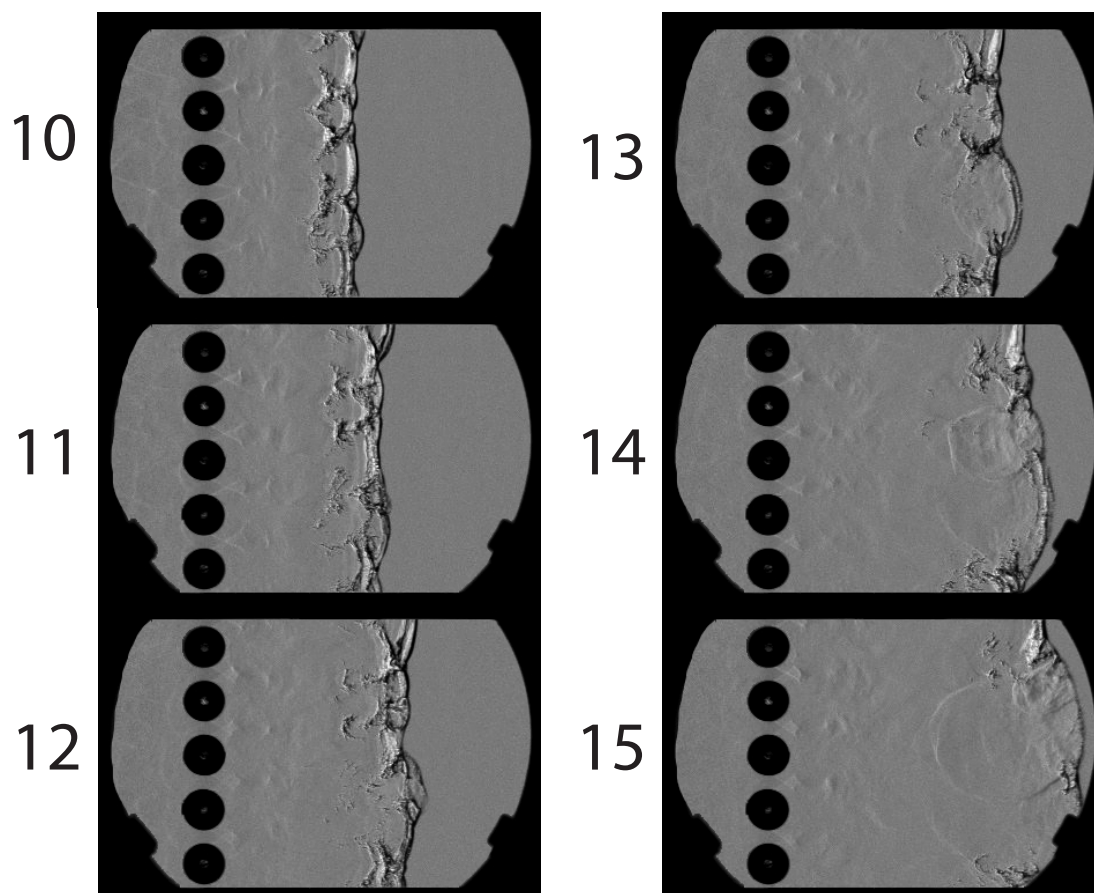


Figure 4.27: Shadowgraph images illustrating the decay of the fast flame in CH_4+2O_2 $p_0 = 17.9$ kPa. Recorded at $11.62 \mu\text{s}$ interframe time, $0.91 \mu\text{s}$ exposure, 86058.51 fps, the full experimental record can be found in Figure F.1.

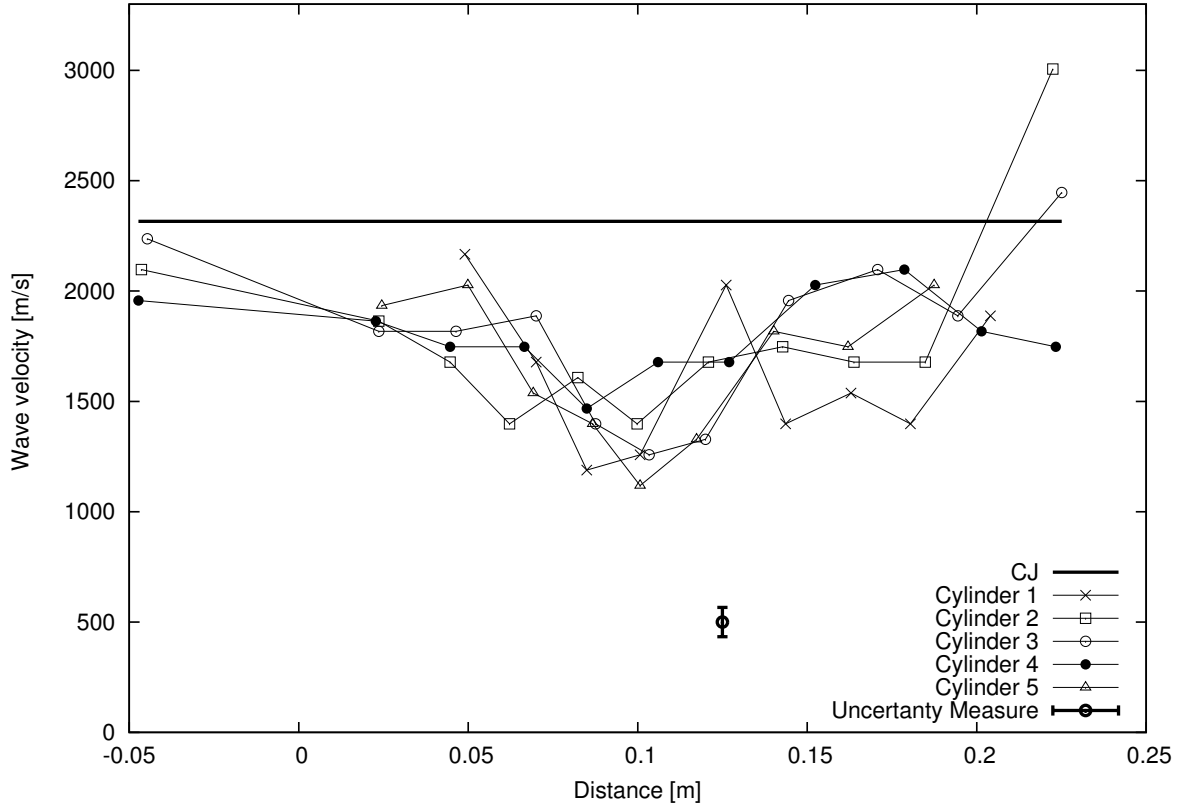


Figure 4.28: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 17.9$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

4.2.2 Shadowgraph Records

Viewing the entire optical section with the shadowgraph system, Figure 4.29 is the record of an experiment with an initial pressure of $p_0 = 9.6$ kPa, and a sensitivity of $b/\lambda \simeq 0.25$. Throughout the early frames, this wave behaves as seen previously. This shadowgraph record, Figure 4.29, shows an early shock-shock reflection strong enough to initiate a detonation in frame 10.

The detonation, in Figure 4.30 envelopes the entire wavefront and develops into a cellular detonation by frame 18. The detonation then continues through the rest of the channel. The velocity profile, seen in Figure 4.31, shows the wave propagating quasi-steadily through the second half of the channel just below the ideal CJ detonation velocity.

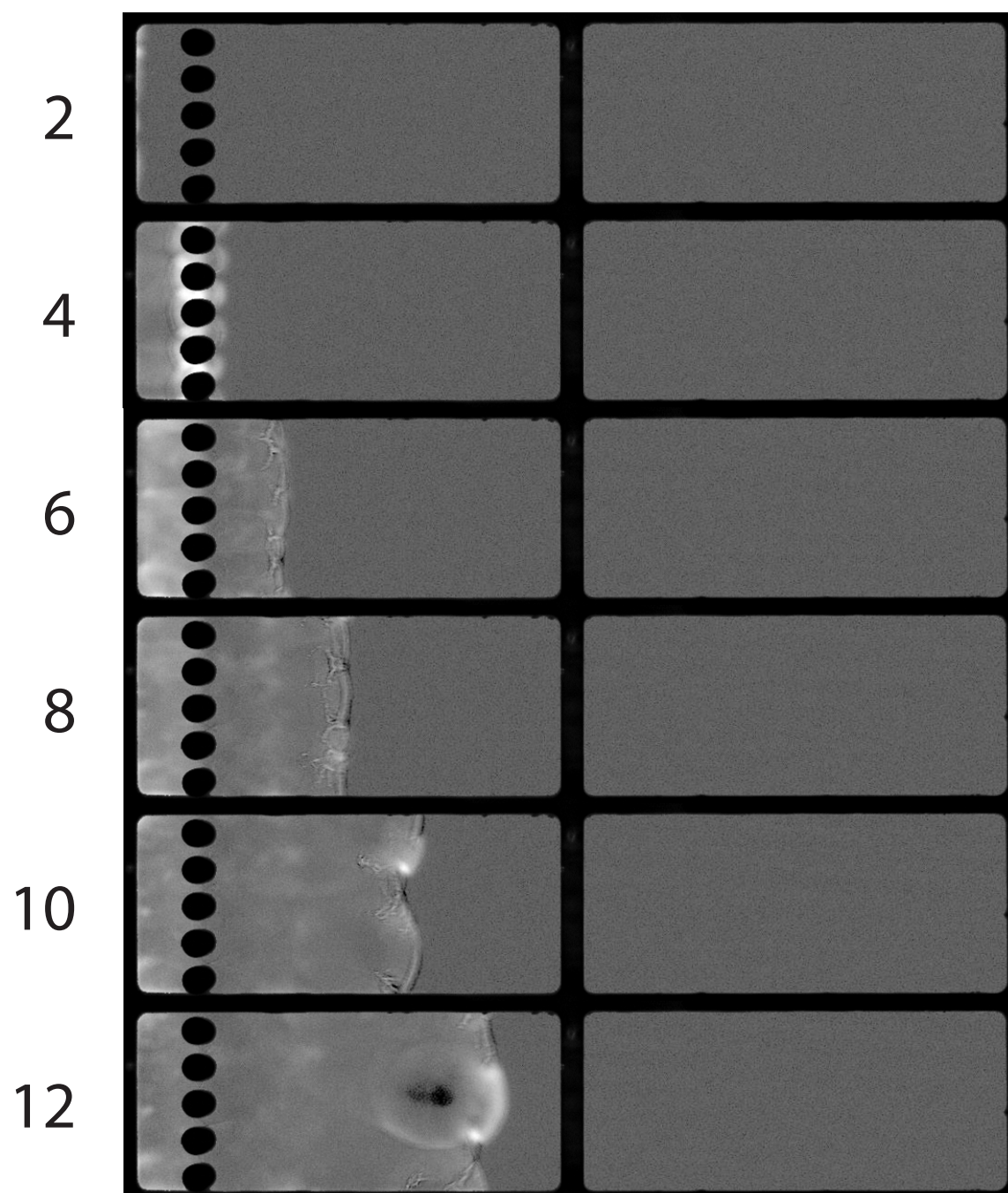


Figure 4.29: Shadowgraph images illustrating the fast flame behaviour in $\text{CH}_4\text{-O}_2$, $p_0 = 9.6$ kPa, recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.8.

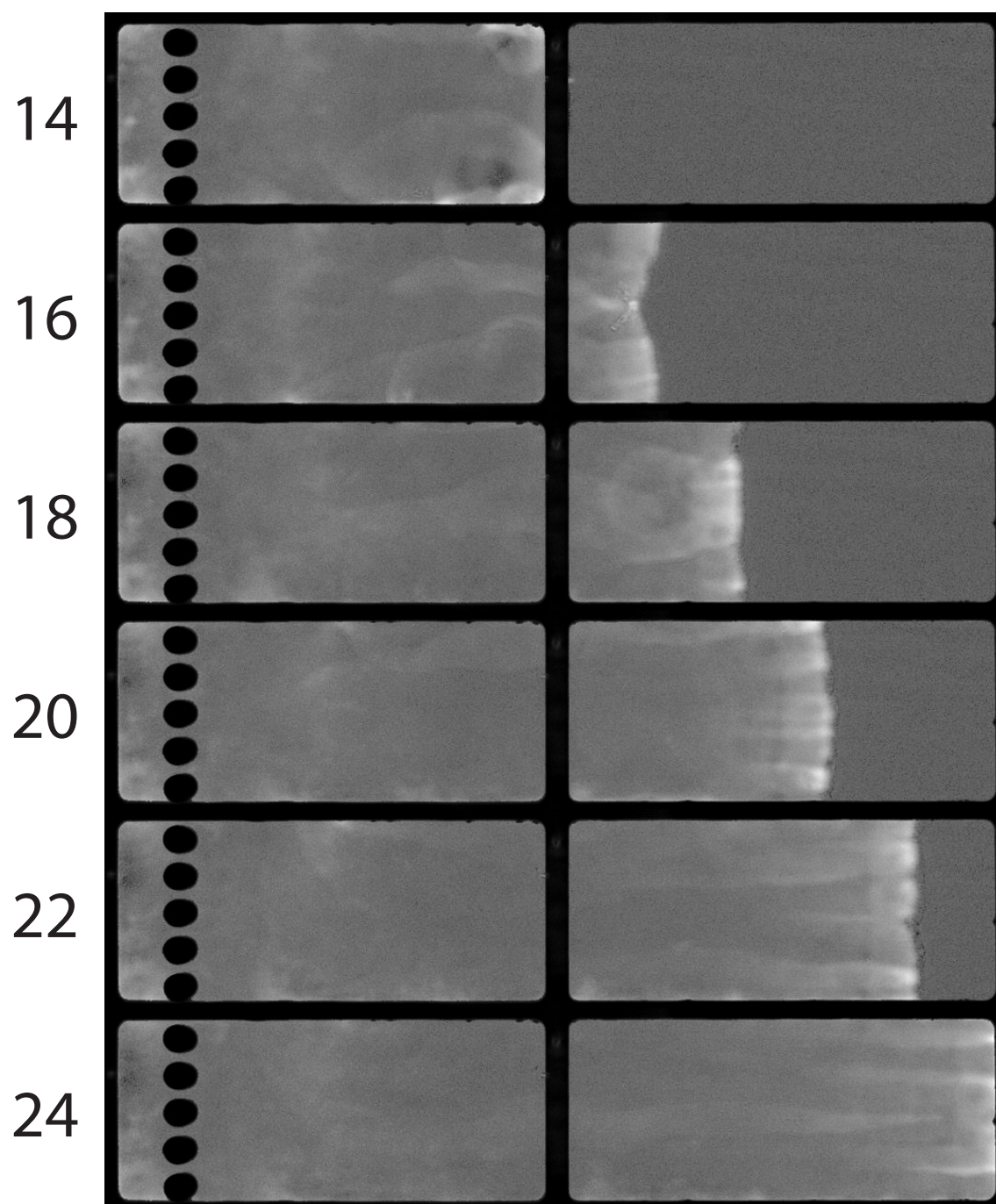


Figure 4.30: Shadowgraph images illustrating the fast flame behaviour in $\text{CH}_4\text{-O}_2$, $p_0 = 9.6$ kPa, recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.9.

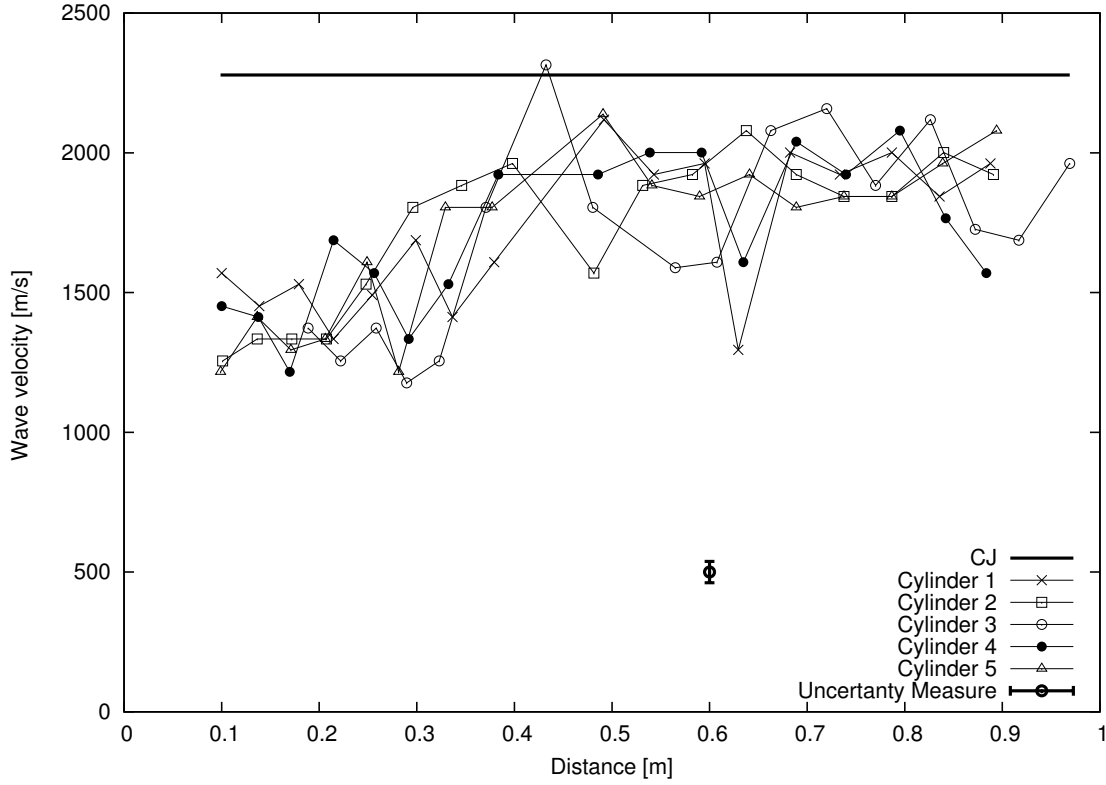


Figure 4.31: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 9.6$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

The regular diffraction pattern caused by the obstacles is quickly overtaken by an asymmetric structure resulting from the reactive shock reflections. This structure persists along the channel, as seen in Figure 4.32, corresponding to $p_0 = 8.2$ kPa and $b/\lambda \simeq 0.14$. Before the wave transition to detonation, the number of transverse waves is reduced. However, the acceleration caused by the reflections of the transverse waves is increased.

Figure 4.32 shows an asymmetric pattern quickly developing after the obstacle interaction. After the wave has proceeded half-way through the channel, Figure 4.33, frame 15, the transverse shock reflection accelerates the new Mach stem ahead of the rest of the wave. The wave reflects in frame 19, causing a new Mach stem to grow until the reflection, seen in frame 21, shows the new Mach stem has transitioned to detonation.

The velocity profile, Figure 4.34, shows the wave has been attenuated by the obstacles at early times. The velocity is maintained until the wave reaches roughly the half-way point through the channel. After this, several large velocity jumps give rise to an overall acceleration of the wave towards the CJ velocity.

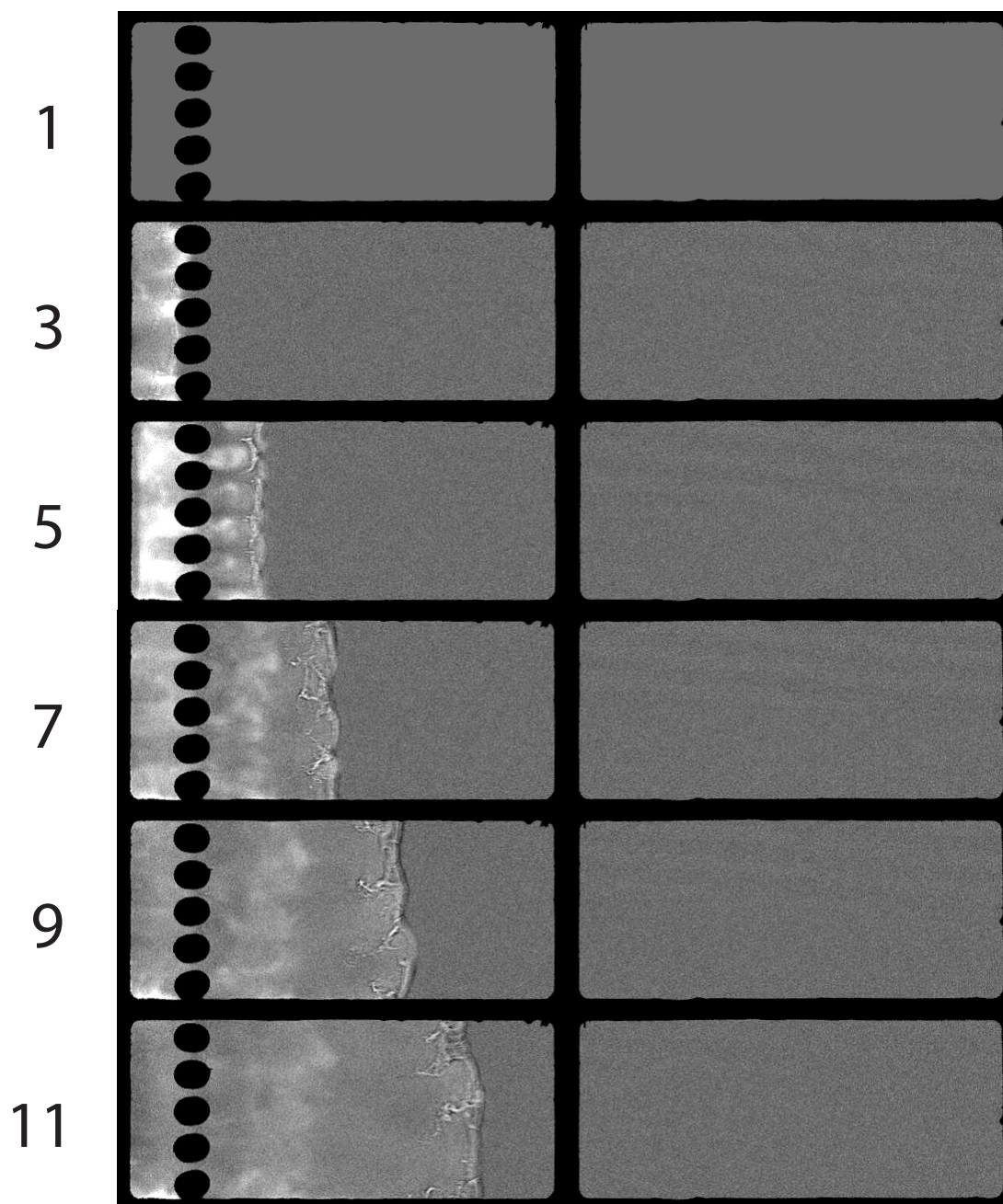


Figure 4.32: Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 8.3$ kPa. Recorded at $25.63 \mu\text{s}$, $4.84 \mu\text{s}$ exposure, 39016.7 fps, the full experimental record can be found in Figures F.6.

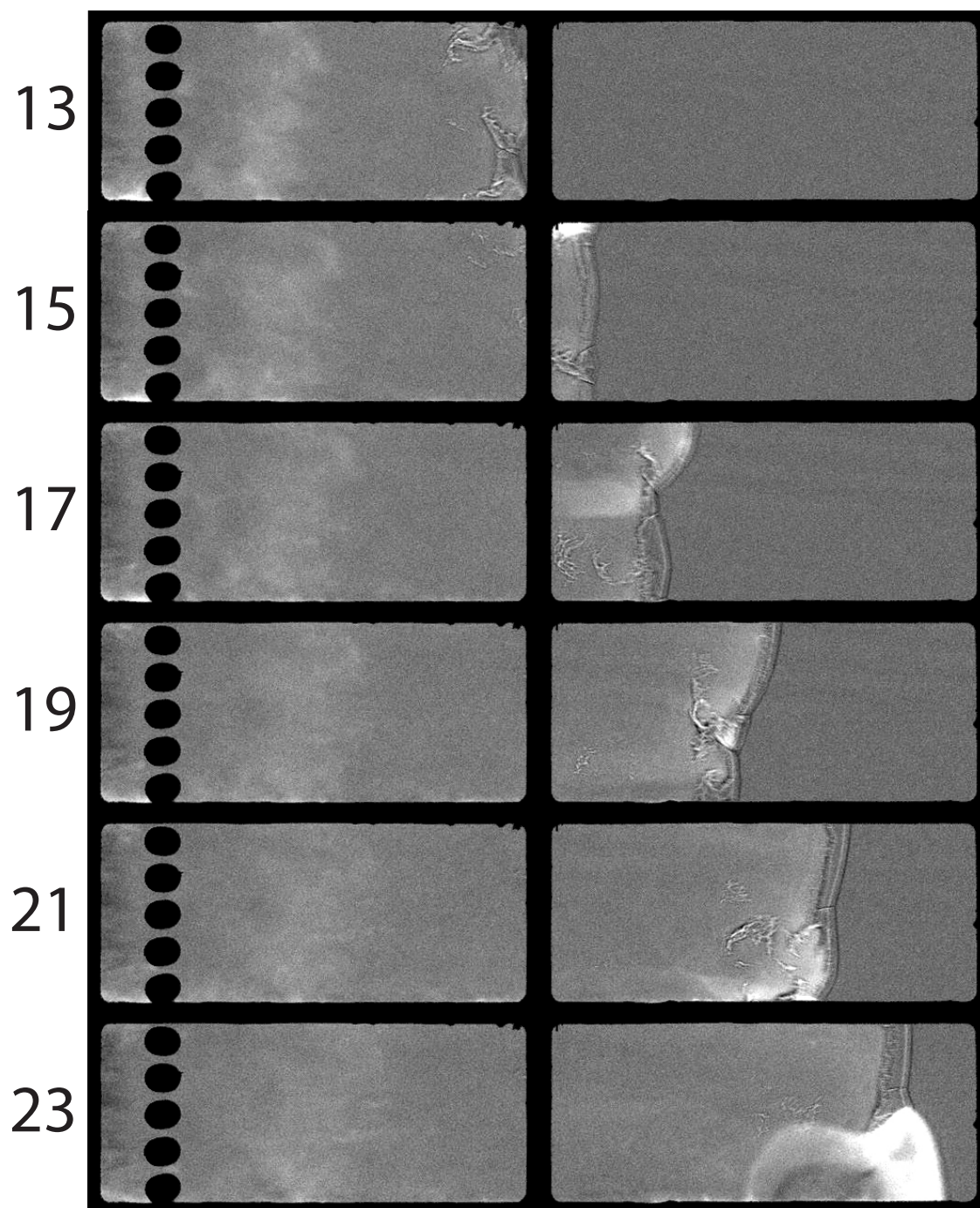


Figure 4.33: Shadowgraph images illustrating the fast flame in CH₄-O₂, $p_0 = 8.3$ kPa. Recorded at $25.63 \mu\text{s}$, $4.84 \mu\text{s}$ exposure, 39016.7 fps, the full experimental record can be found in Figures F.6.

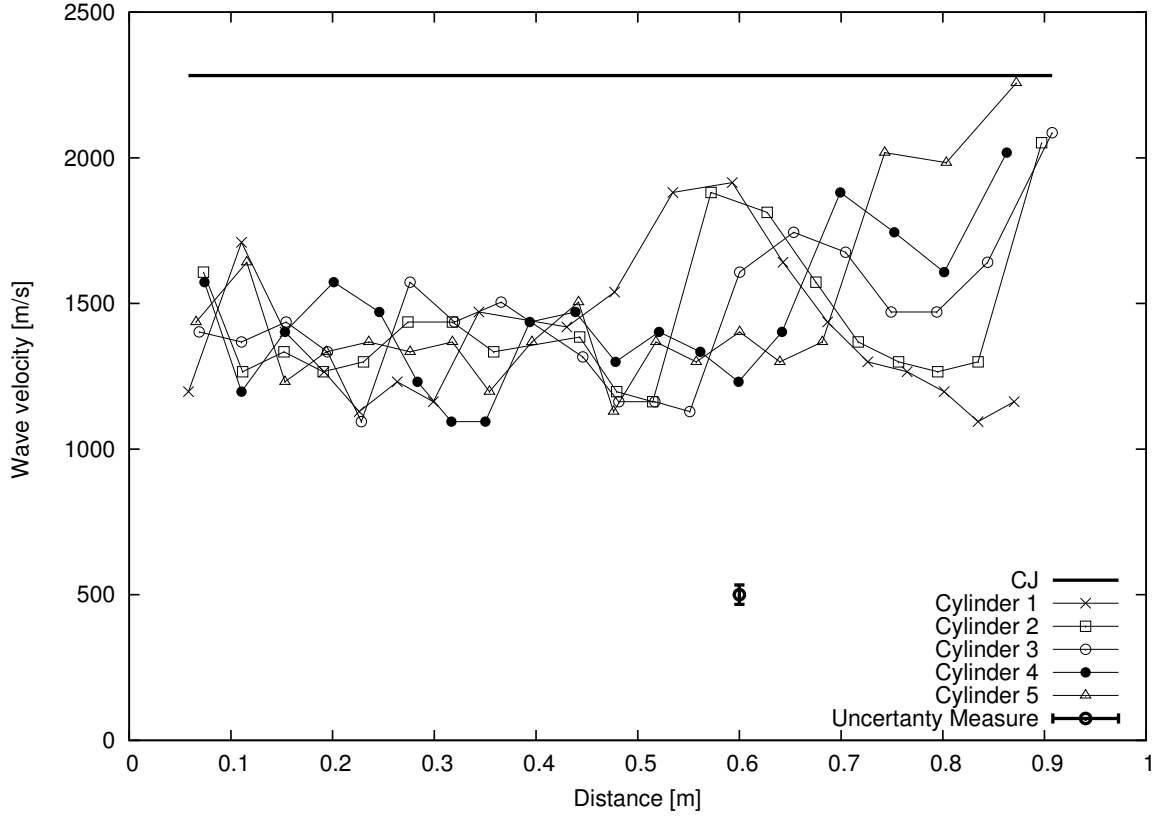


Figure 4.34: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 8.3$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

Figure 4.35 shows the record of an experiment conducted at a slightly higher initial pressure, corresponding to $p_0 = 7.6$ kPa and $b/\lambda \simeq 0.12$. This experiment is very interesting as the structures allow a clearer view of the events. We will examine this experiment in detail. The detonation enters from the left. Frame 2 shows the high amount of self-luminosity of the cellular detonation. Examining the frames in Figure 4.35, the first shock-shock reflection seen in frame 4 occurs as a result of the shock diffraction around the obstacle. A hotspot behind the newly formed Mach stem is generated. The symmetrical structure breaks down by the sixth frame.

The first hotspot drives the newly formed Mach stem to overtake the incident wave, causing transverse wave reflections and a second generation of hotspots, Figure 4.36 frame 7 and 8. The breakdown of the symmetric pattern created by the obstacles continues. This structure is characteristic of the fast-flame regime. As the wave continues along the channel, it begins to develop fewer transverse waves. Frame 12 of Figure 4.36 shows

the result of a shock-shock reflection seen in frame 10 in the center of the channel. The keystone structure seen in frame 12 shows a thin wave structure and it leads the rest of the wave.

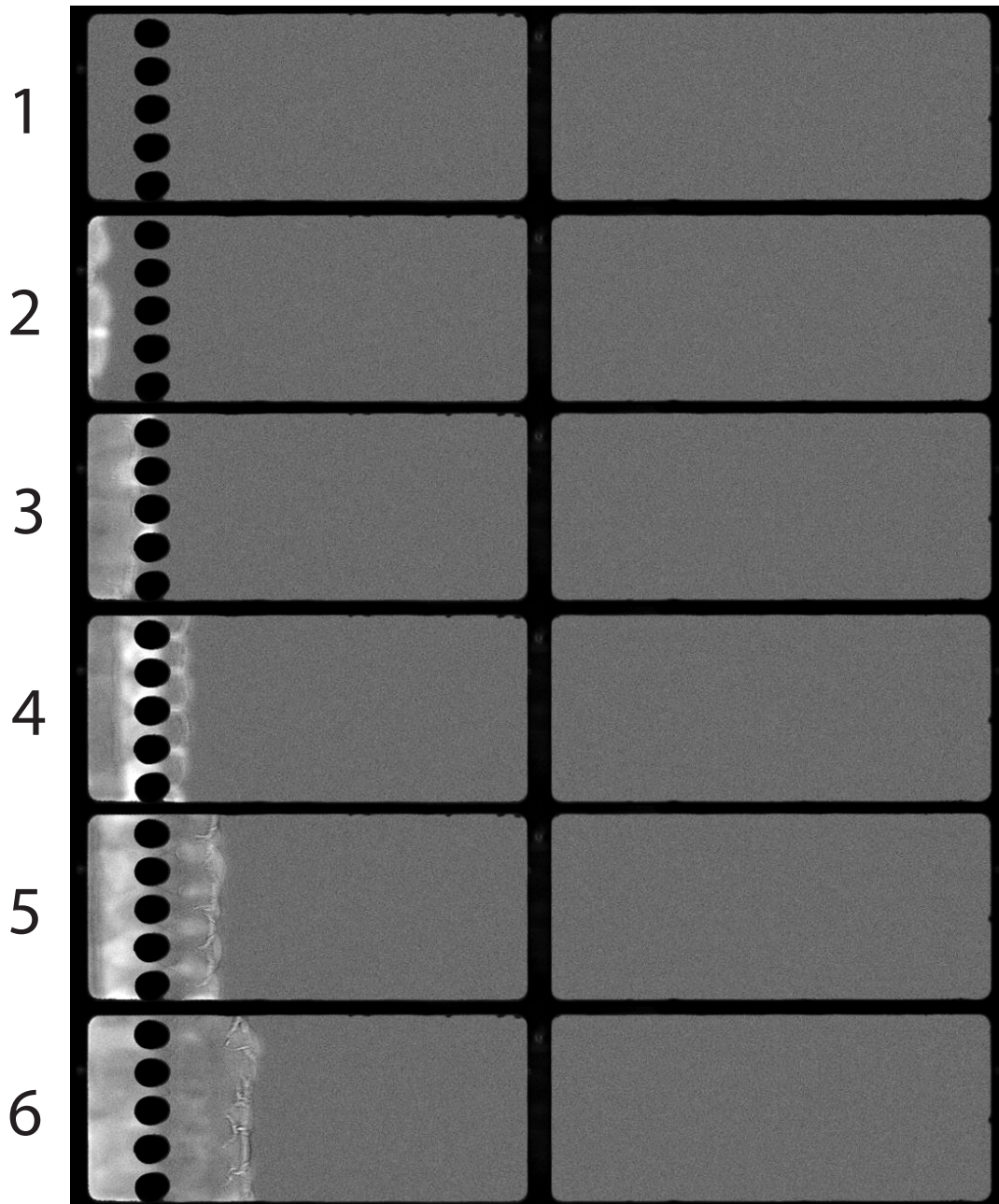


Figure 4.35: Part 1 of Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.4 & F.5.

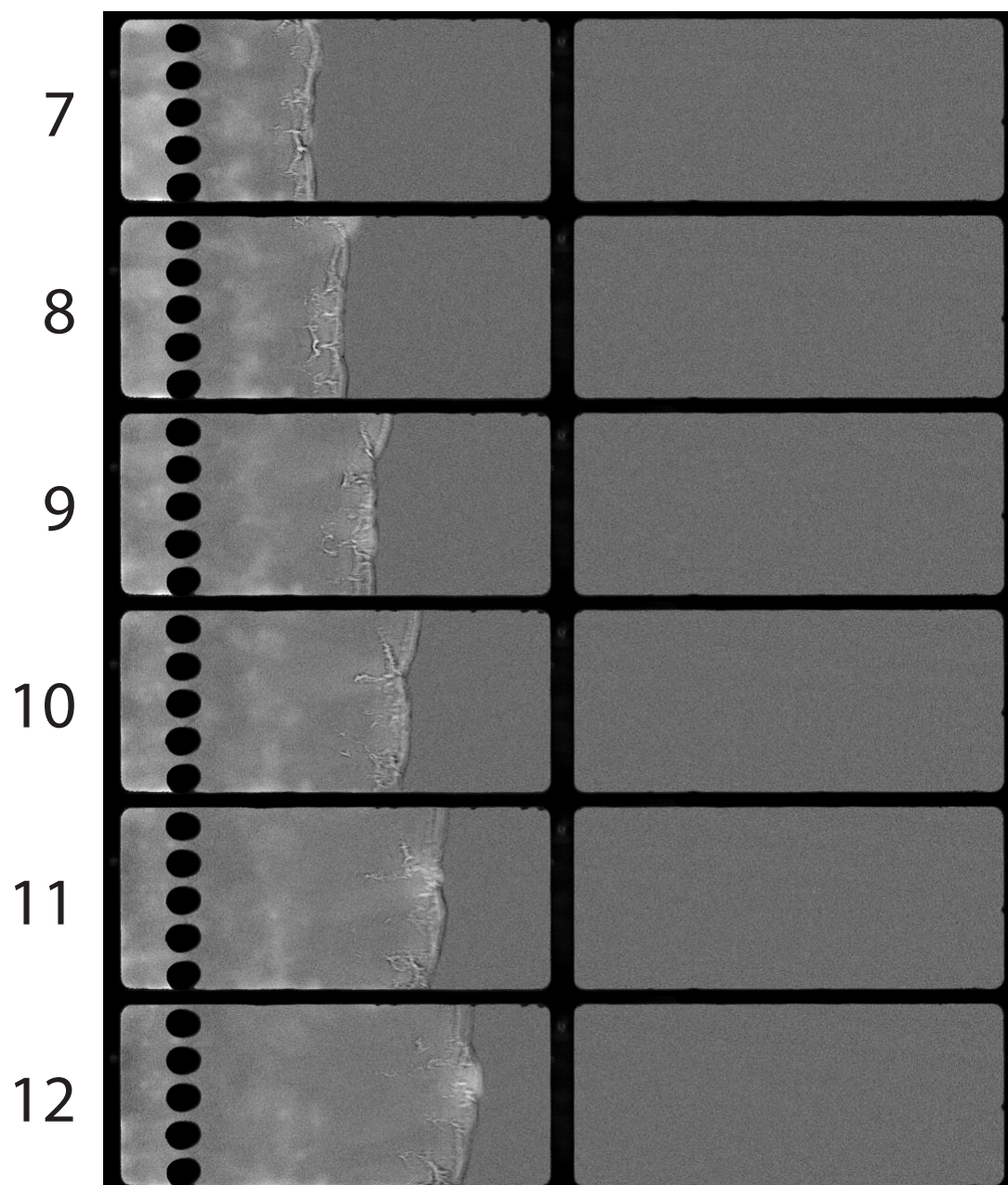


Figure 4.36: Part 2 of Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.4 & F.5.

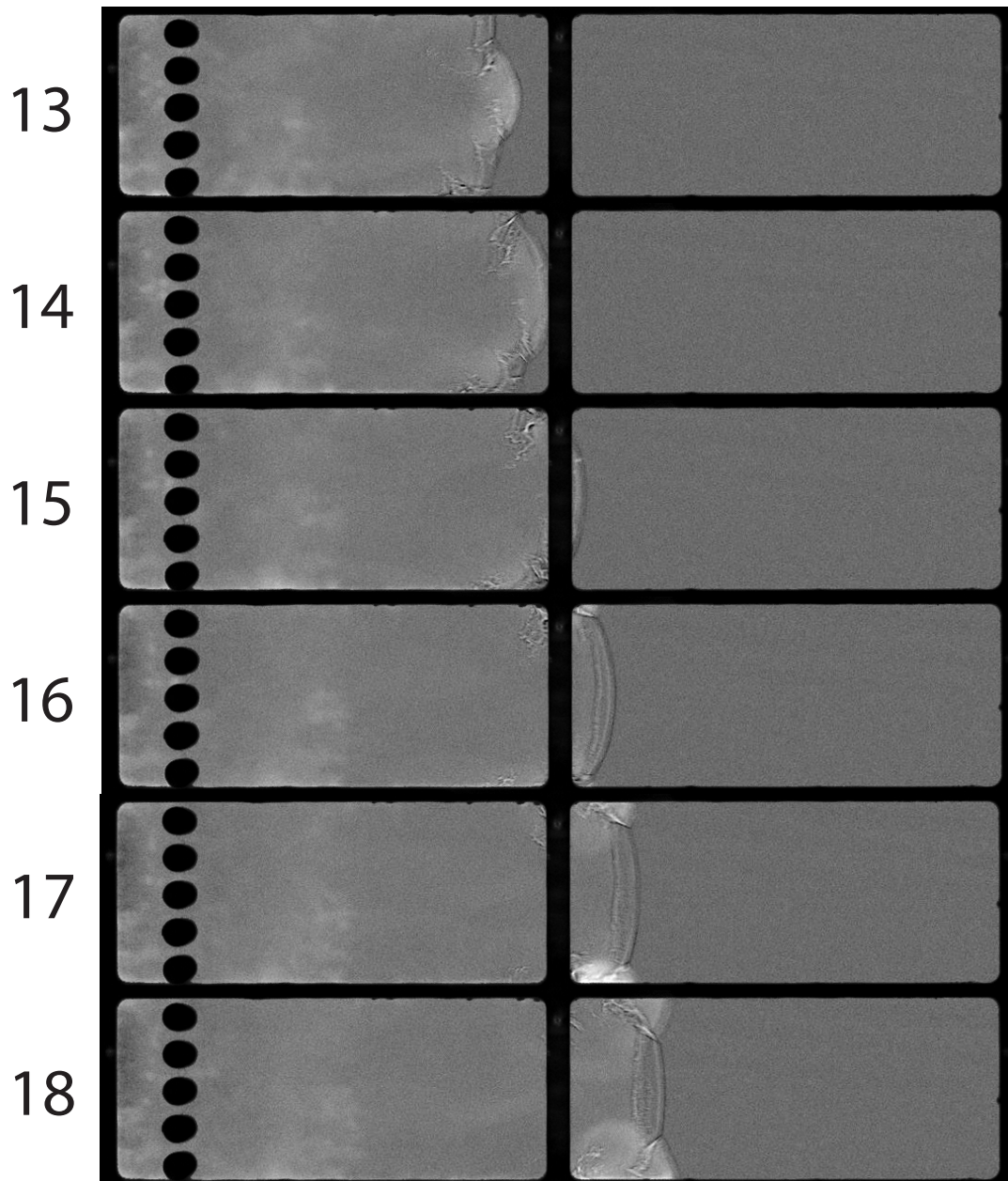


Figure 4.37: Part 3 of Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.4 & F.5.

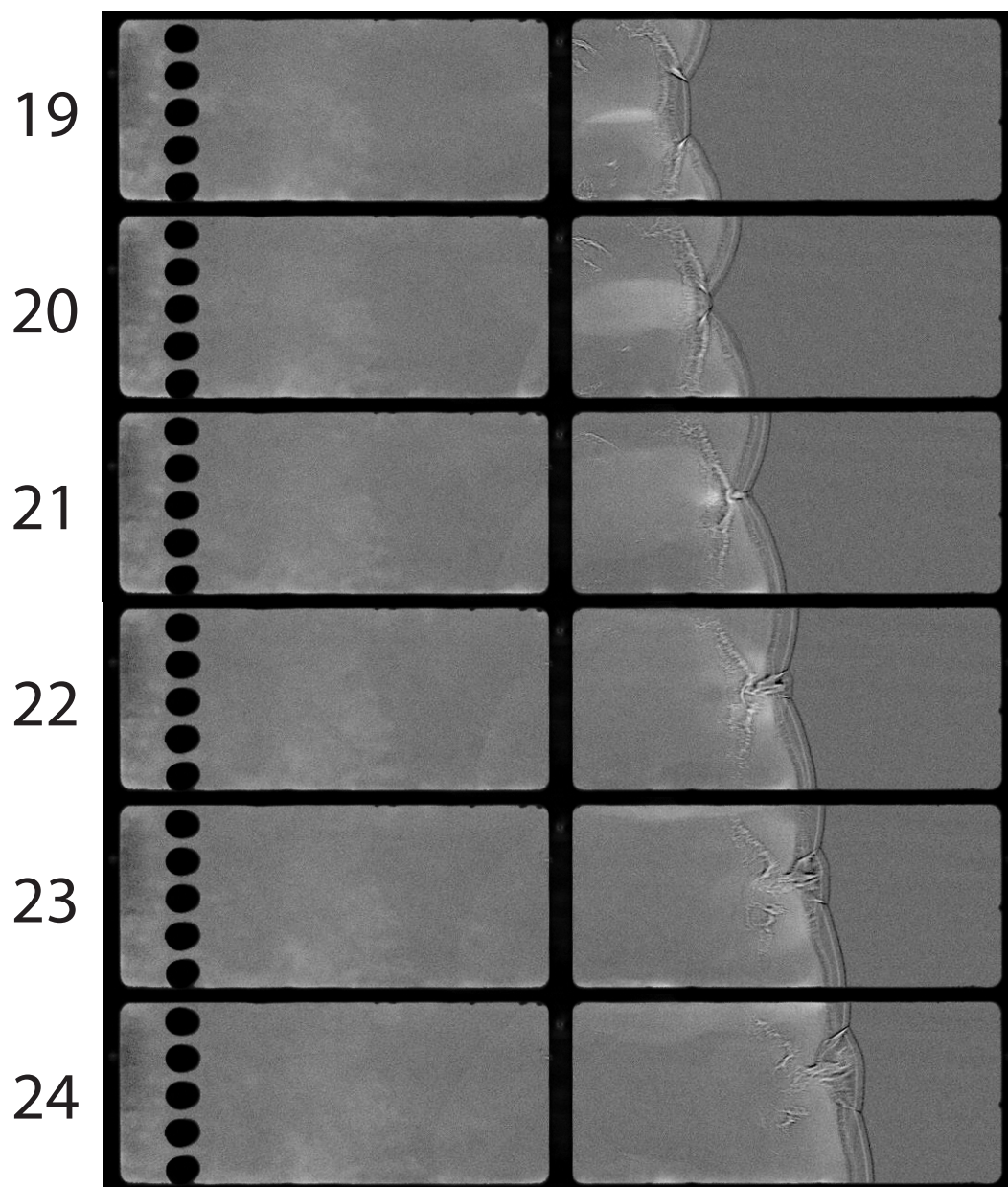


Figure 4.38: Part 4 of Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.4 & F.5.

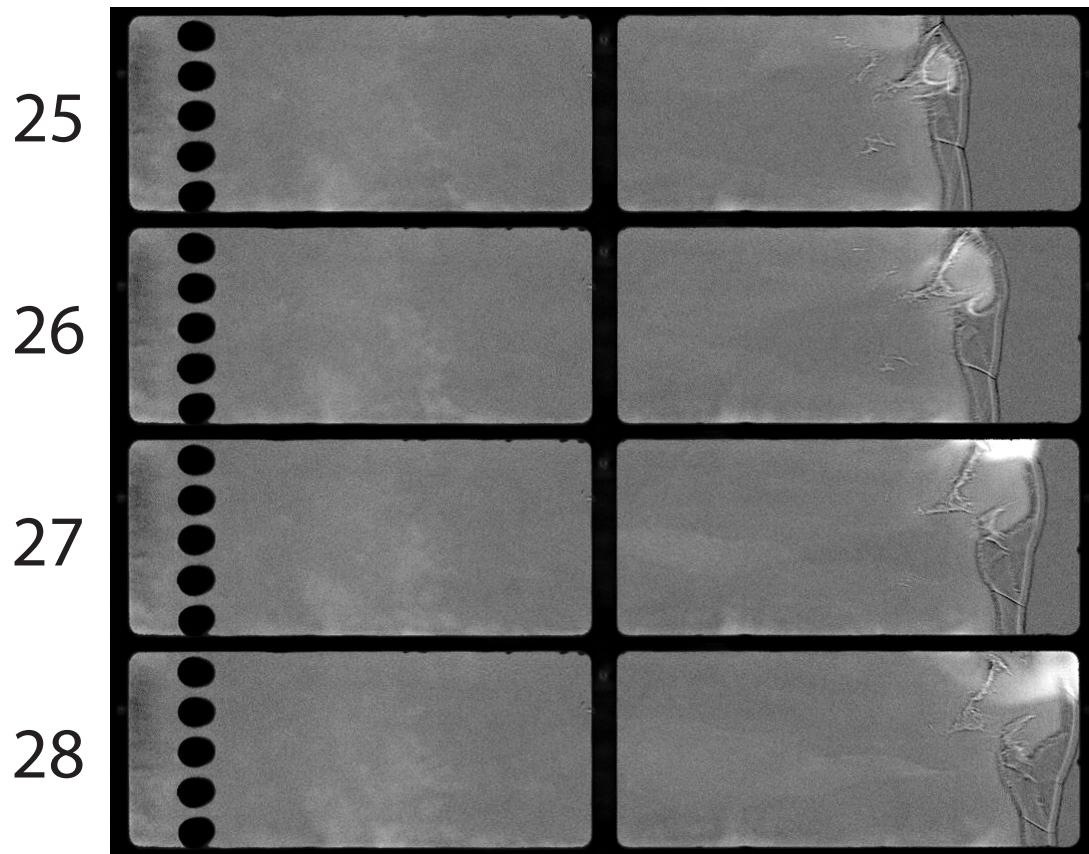


Figure 4.39: Part 5 of Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.4 & F.5.

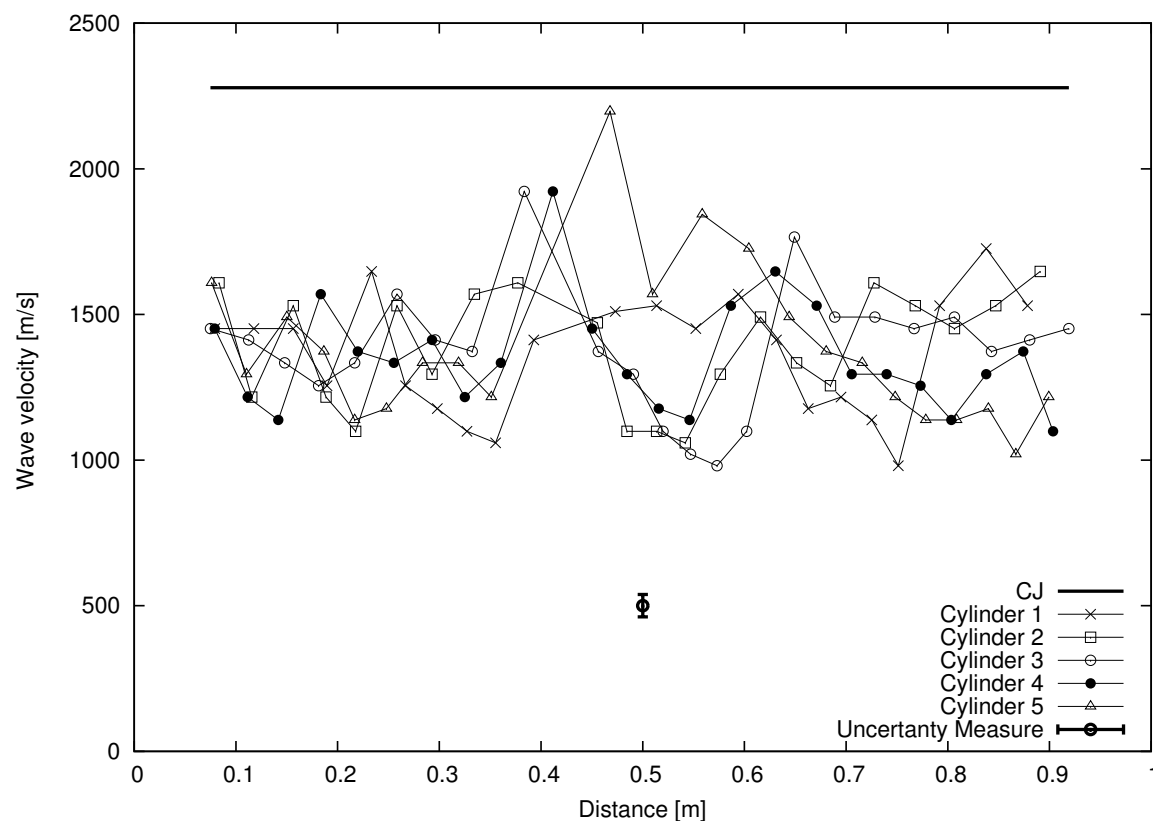


Figure 4.40: Velocity record from the above shadowgraph record of methane-oxygen $p_0 = 7.6$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

The result of these shock reflection accelerates Mach stems ahead of the rest of the fast flame, driving transverse waves in both directions expanding to fill the entire channel, seen in Frame 13 of Figure 4.37. When these transverse waves reflect against the top and bottom wall, the shock-wall reflections form hot spots indicated by the reacted pockets behind the resulting Mach stems, seen in frames 17 & 18. The fast flame has been reduced to two transverse waves.

Figure 4.38 frame 19 & 20 show these two transverse waves before the shock-shock reflection. After the reflection in frame 20, a new Mach stem begins to expand braced by the two transverse waves. Behind the new Mach stem a striated burning pattern is observed in frame 23, Figure 4.38. This region exhibit signs of a forward jetting effect. Frame 23 and 24 show evidence of combusted gas entering the roll-up of the slip line behind the Mach stem. Between frame 24 and 25 the region behind the Mach stem is combusted.

Figure 4.39 frame 25 exhibits the pattern of an asymmetrical forward jetting of the slip line. The top half displays a vortex-like structure where the inner section has been burned. Figure 4.39 frame 27 shows a large amount of self-luminosity and a large jump forward from the position in frame 26. The self-luminosity seen in frame 27 & 28 is indicative of detonation initiation by the upper reflection of the transverse wave.

The velocity profile seen in Figure 4.40 shows many short oscillations at early times. A large coherent oscillation is observed in the center of the channel. As the wave continues to the end of the channel, frame 27, the self-luminosity is indicative of detonation initiation; however, by frame 28 the lead shock is out of the field of view therefore the increase in velocity is not seen in the velocity profile.

Figure 4.41 is the record of an experiment at $p_0 = 6.9$ kPa corresponding to a $b/\lambda \simeq 0.1$. The initial CJ detonation interacts with the five cylindrical obstacles. As the detonation attenuates around the cylinders, the shock and reaction zone decouple. The decoupled shock diffracts around each cylinder causing a shock-shock reflection in the wake. By frame 8 the number of transverse waves is reduced. This structure continues downstream. Frame 12 shows the oscillation in velocity of the lead shock wave. Where the distance between the lead shock and end of the reaction zone is longer, that segment of the lead shock trails. Where the thickness of the wave is thin, the lead shock proceeds ahead.

Figure 4.42 frame 16 shows a reacted keystone structure following a reflection with the bottom wall. The number of transverse waves has been reduced. Frame 20 shows the results of a transverse wave reflection. Reacted gas protrudes into the region behind the new Mach stem. By frame 24 a large portion of the region behind the Mach stem is reacted and this shows a roll-up at the interface between reacted and un-reacted gas below the transverse wave. The 28th frame shows a large increase in self-luminosity usually indicative of a detonation initiation.

After each shock reflection, each new Mach stem forms a hot spot, causing the velocity jump as seen in figure 4.43. Each reflection increases the local speed of the wavefront followed by a slow decay in wave velocity between each successive reflection. The next reflection then re-invigorates the velocity. In this case, the velocity decay in sections of the wave is unable to decrease the local wave speed enough for the subsequent reflection to fail in the creation a new generation hotspots.

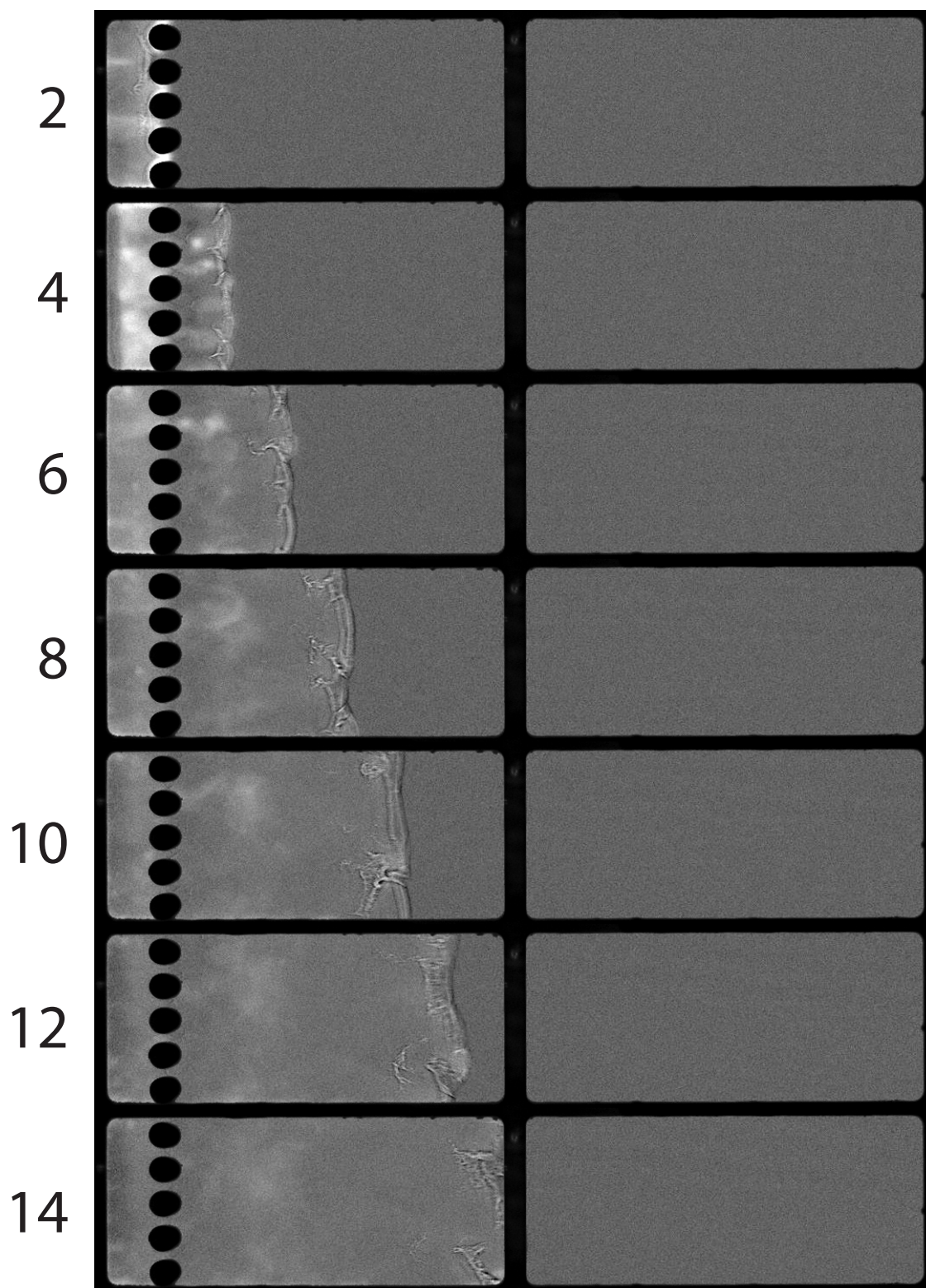


Figure 4.41: Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 6.9$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.2 & F.3.

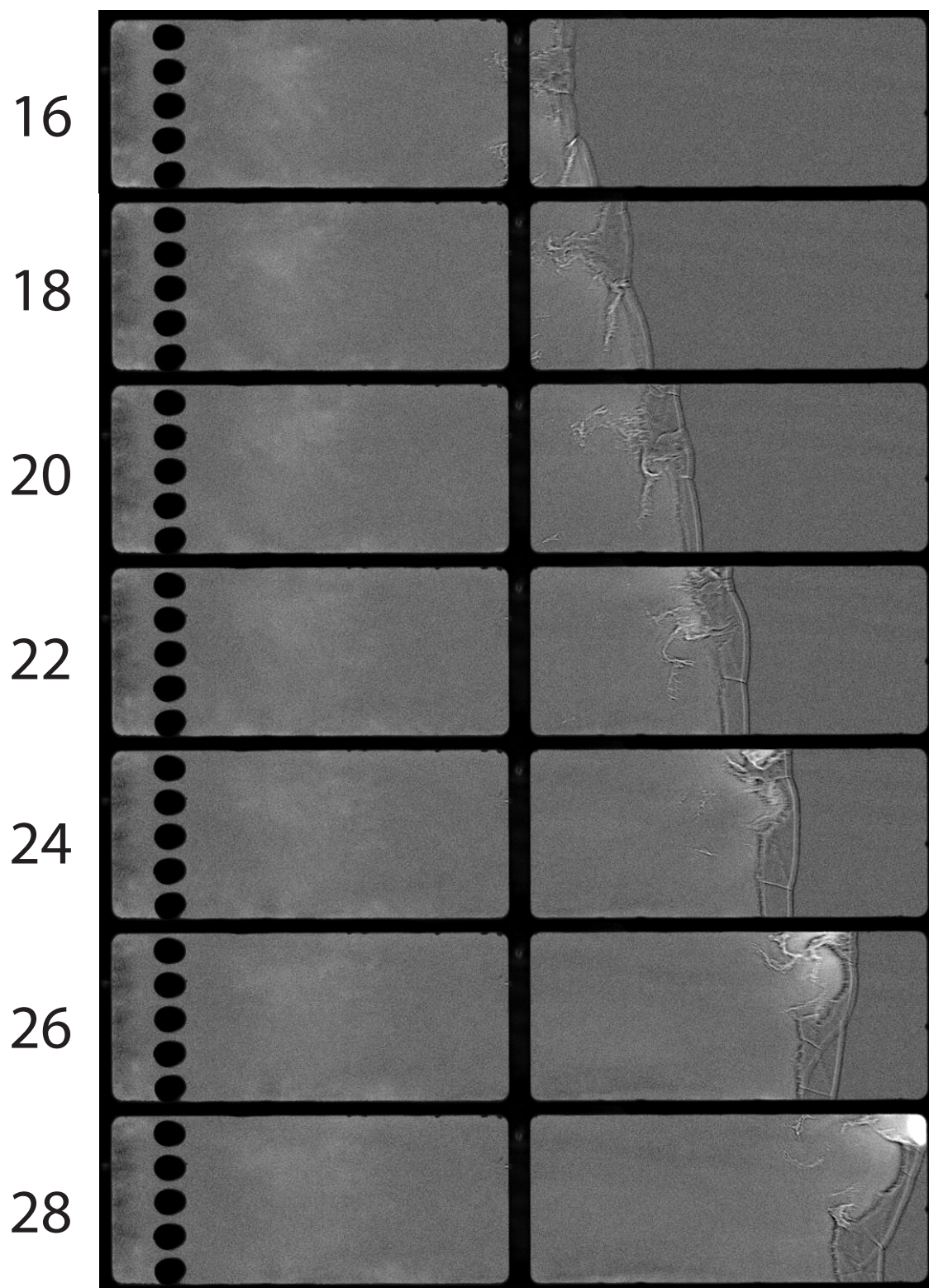


Figure 4.42: Shadowgraph images illustrating the fast flame in CH₄-O₂, $p_0 = 6.9$ kPa. Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps, the full experimental record can be found in Figures F.2 & F.3.

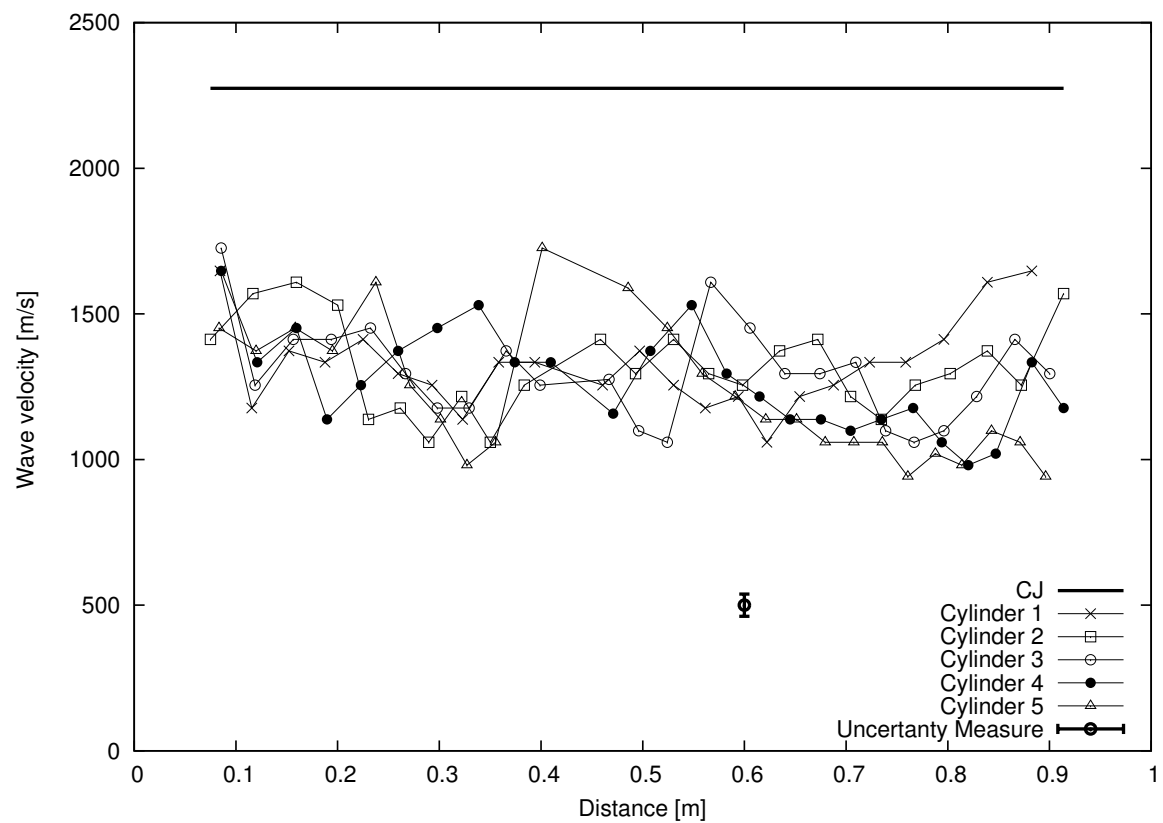


Figure 4.43: Velocity record from the above shadowgraph images of methane-oxygen $p_0 = 6.9$ kPa. Error bar represents average uncertainty measurement aggregated across the entire experiment.

Chapter 5

Discussion

5.1 Analysis

As we have seen above, both hydrogen-oxygen and methane-oxygen display very different behaviour in the wake of the cylinders. Here we will explore the different properties of the mixtures to gain a better understanding of the origin of the behaviours displayed by the different gas mixtures. We can divide the various properties into three different groups, the shock dynamic properties, the chemical kinetic properties and the hydrodynamic properties. For this analysis we will examine the shock-shock reflections taking place behind the cylinder, specifically Figures 3.4 and 4.1, which are representative of the general behaviour of each gas mixture.

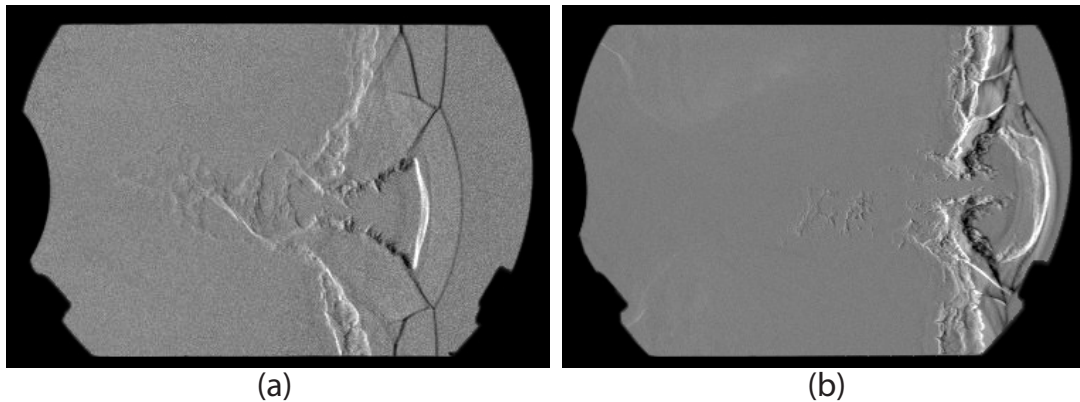


Figure 5.1: A comparison of reflection behaviour between, (a) hydrogen-oxygen at $p_0 = 11.0$ kPa and (b) methane-oxygen at $p_0 = 8.3$ kPa. Details can be found at Figures 3.4 & 4.1, respectfully.

The shock dynamic properties are the aspects of the shock waves which we can directly estimate from the experimental records and the shock jump equations. These properties are estimated along the centreline. Changes between frames use the position of the shock wave and the interframe times to find the approximate shock velocities. For each case the Mach stem was initially travelling at approximately 70% of the Chapman-Jouguet velocity after the reflection (Figures 3.5 & 4.2). Using these velocities, the post shock thermodynamic state was found calculating frozen chemistry with real specific heats using the NASA's Chemical Equilibrium with Applications (CEA) code [39].

The chemical kinetic parameters, ignition delay, characteristic energy deposition time, and effective activation energies were calculated by conducting constant volume homogeneous reactor calculations using the CANTERA code [40]. A realistic chemical model optimized for each test mixture was used for each calculation, specifically the GRI 3.0 high temperature chemical kinetic mechanism for methane [41] and the Li et. al. [42] mechanism for hydrogen. The ignition delay (t_{ig}) is measured from the point when the gas mixture is suddenly heated to the inflection point (maximum slope) of the rise in temperature, where we define ignition, seen in Figure 5.2. The characteristic energy deposition time (t_{reac}) is defined mathematically as follows and is represented graphically in Figure 5.2,

$$t_{reac} = \left(\frac{d \ln T}{dt} \right)^{-1} \quad (5.1)$$

The effective activation energies were found by calculating the ignition delay at the relevant temperature, as well as perturbing this temperature by 100 degrees in order to find the exponential sensitivity using an Arrhenius plot ($1/T$ versus $\ln(t_{ig})$) where the slope of this plot is $-Ea/R$. This is a common way of calculating the reduced activation energy Ea/RT_s [43].

The laminar flame speed in the shocked un-reacted gas was also estimated with the Cantera code. The isentropic exponent as well as the physical properties such as density and kinematic viscosity in the gases were calculated assuming frozen chemistry at the post-shock condition using the CEA code. The velocity difference on the slip line was calculated using triple shock analysis matching pressures across the slip line under the assumptions of a perfect gas as described by Ben-Dor [44]. These properties are listed in Table 5.1.

Table 5.1: Thermo-chemical properties of the gas behind the Mach shocks in hydrogen-oxygen and methane-oxygen experiments 3.4 & 4.1, respectfully.

		Hydrogen-Oxygen	Methane-Oxygen
Pre-shock conditions			
Initial Pressure [kPa]	p_0	11.0	8.3
Detonation Sensitivity	b/λ	1.14	0.73
Shock Dynamic Properties			
Mach Shock Strength	M_S	3.5	4.5
Shock Velocity [m/s]		1912	1598
Post-Shock Temperature [K]	T_s	980	1105
Post-Shock Pressure [kPa]	p_s	207	209
Post-Shock Speed of Sound[m/s]		959	643
Induced Flow Velocity[m/s]		243	426
Chemical Kinetic Properties			
Reduced Activation Energy	$\frac{E_a}{RT_s}$	37	17
Ignition Delay [μs]	t_{ig}	4.5×10^3	1.57×10^4
Reaction Time [μs]	t_{reac}	0.46	0.47
Instability Parameter χ	$\frac{E_a}{RT_s} \frac{t_{ig}}{t_{reac}}$	5.7×10^5	3.6×10^5
Laminar Flame Speed [m/s]	S_L	64	17
Hydrodynamic Properties			
Isentropic Exponent	γ	1.36	1.22
Kinematic Viscosity [m ² /s]	ν	1.4×10^{-4}	7.8×10^{-5}
Velocity Difference on Slip Line [m/s]	Δv	581	512
Unburned/Burned Density Ratio	$\frac{\rho_u}{\rho_b}$	2.78	3.76

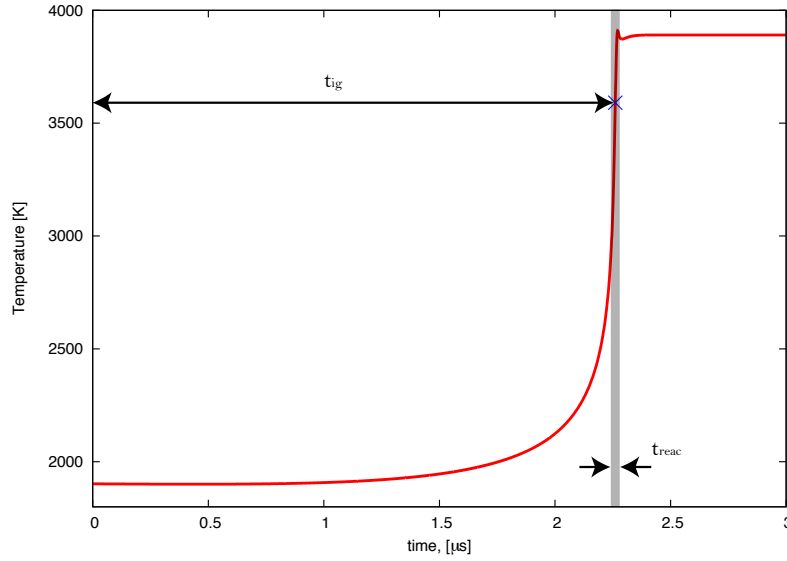


Figure 5.2: Example of methane-oxygen ignition delay calculations depicting the parameters t_{ig} and t_{reac} .

5.1.1 Chemical Kinetics

In the past it has been suggested that propensity for fast flames can be correlated with the propensity to form hot spots [6, 29, 45, 46]. Following unstable detonation theory this is denoted by large reduced activation energies. The activation energy of the shocked hydrogen-oxygen gas is higher ($\frac{Ea}{RT_s} = 37$) than that of methane-oxygen ($\frac{Ea}{RT_s} = 17$). If unstable detonation theory were applicable, this would suggest that the hydrogen-oxygen mixture was more likely to generate hotspots.

More recently, unstable detonations have been correlated with a high χ value,

$$\chi = \frac{t_{ig}}{t_{reac}} \frac{Ea}{RT} \frac{Q}{RT} \quad (5.2)$$

defined as the product of the reduced activation energy, the ratio of induction time to reaction time and the reduced heat release [47, 46, 48]. Table 5.1 shows the calculated values of χ for the relevant cases here discussed. Examining the calculated values of χ shows that the hydrogen-oxygen is higher with a value of 5.7×10^5 compared to 3.6×10^5 for methane-oxygen. Although, the magnitude of these parameters indicate that hot spots with strong pressure generation will form in both mixtures [48, 46], the similarity between these values does not allow discrimination between the two mixtures. This suggests that the fundamental behavioural differences between the two mixtures observed

in our experiments cannot be explained using propensity for hot spot formation theory as previously understood.

If the fast flame was controlled by auto-ignition as in a classical regular detonation, then the mixture with the shortest ignition delay would be expected to show the higher propensity for fast flames. In this case, the ignition delay would dictate the separation distance between the lead shock and the flame. However, the calculations at the relevant conditions predict a shorter ignition for the hydrogen-oxygen mixture, $t_{ig} = 4.5 \times 10^3 \mu\text{s}$ compared to that of methane-oxygen, $t_{ig} = 1.57 \times 10^4 \mu\text{s}$. The contrary is observed in the experimental records where we see an ever-growing shock-flame distance in the hydrogen-oxygen experiments whereas methane-oxygen maintains a close distance between the shock and flame.

To better understand what is controlling the distance between the lead shock and the flame, calculations were performed to estimate the flame speed in the shocked gas. Again, the experimental evidence shows the opposite trend from what is calculated: the predicted laminar flame speed in hydrogen-oxygen (64 m/s) is higher than that of methane-oxygen (17 m/s).

Adding the flame speed to the induced gas velocity behind the shock wave shows that laminar flame speed would be unable to travel at the wave speeds observed experimentally. The wave speed of hydrogen-oxygen is 1912 m/s, and the estimated induced flow velocity is 243 m/s. The same picture is seen in the methane-oxygen mixture where the wave speed is 1598 m/s, and the estimated induced flow velocity is 426 m/s. Thus, the laminar heat diffusion is not the dominating propagation mechanism.

The required parameters for a turbulent flame analysis across the entire fast flame have not been measured or fully modelled. Therefore, no definitive conclusions can be drawn on the subject. However, the experimental evidence seems to indicate fast flame decay between successive shock reflections. These shock reflections provide a jump in velocity required for the wave to remain quasi-steady. Further work on this subject is needed.

Together this information indicates that diffusion is unlikely to be the dominating mechanism responsible for the fast flame propagation. Chemical kinetic properties are therefore unable to act as the dominating parameters controlling the propagation of the fast flames. To elucidate the controlling parameters, the next avenue to examine is the hydrodynamics of the different mixtures.

5.1.2 Hydrodynamics

The hydrodynamic properties of the mixtures are investigated to discover the origin of the fast flame behaviour. Table 5.1 shows that the specific heat ratio of the hydrogen-oxygen mixture ($\gamma = 1.36$) is higher than that of the methane-oxygen mixture ($\gamma = 1.22$).

Recently, Mach and Radulescu extended the arguments previously made by Hornung [49] and Henderson [50] to show that for mixtures with lower specific heat ratios, more prominent forward jetting of the slip line will occur in Mach reflections [1]. Mach determined that isentropic exponents, high incident shock Mach numbers, and large reflection angles lead to pressure build-up behind the Mach stem along the stagnation streamline, causing a forward jetting effect. Semenov et. al. [51] have argued differently, namely that the forward jetting effect is due to the deflection process of the incident shock-induced flow along the reflection surface where the specific heat ratio controls the density ratio. The larger density ratios would cause thinner regions of dense gas along the reflection surface to push the contact surface forward creating the forward jetting structure. This behaviour is much less prominent in gases with higher isentropic exponents.

Good agreement is found when comparing the experimental records of the Mach reflections and the prediction correlating the lower isentropic exponent with the prominent forward jetting. Figures 5.3 & 5.4 show examples of the inert transitional Mach reflections exhibited by both hydrogen-oxygen and methane-oxygen. This shows the prominent jet exhibited by the methane-oxygen and the lack of the forward jet in the hydrogen-oxygen without the effects of combustion.

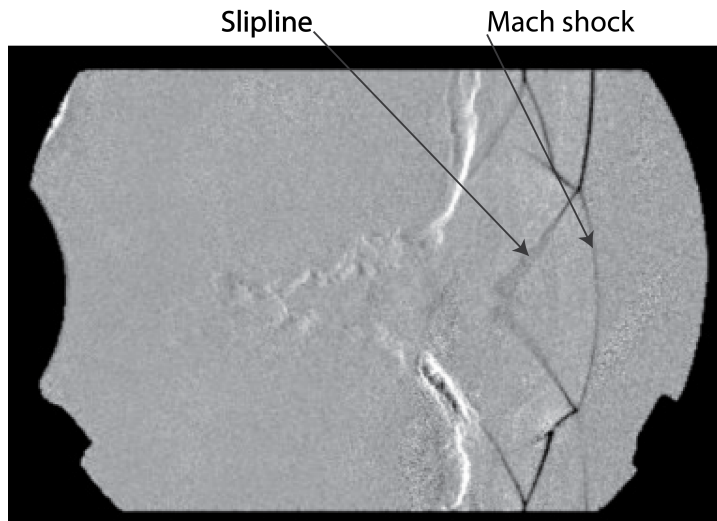


Figure 5.3: Inert shock reflection pattern in $2\text{H}_2\text{-O}_2, p_0 = 10.3 \text{ kPa}$.

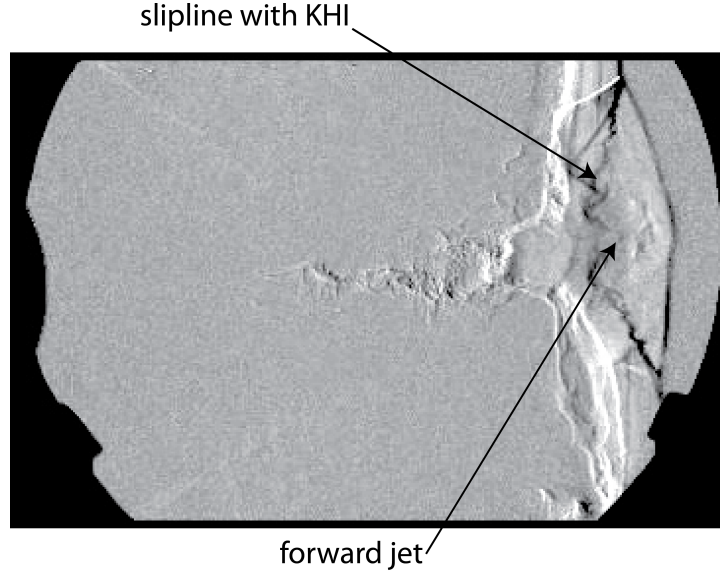


Figure 5.4: Inert shock reflection pattern in CH_4+2O_2 ; $p_0= 3.44$ kPa.

The largest fundamental difference which has been consistently observed throughout the experimental records of this study is the forward jetting behind the Mach reflections. The experimental records show that for both reactive and un-reactive irregular reflections of the lead shock, exhibited by Figures 4.38, 4.16, 4.1, 4.3, 4.5 and 4.19, methane-oxygen consistently displays a more prominent forward jet compared to that of hydrogen-oxygen. This agrees with the findings correlating the forward jetting with the lower isentropic exponent.

We have numerically calculated the inert shock reflection problem in an inert gas using the perfect gas approximation to gain a better understanding of the experimental results. These calculations follow the work described in [31], [1], [52] and as shown in [53], using Amrita computational package [54]. These Euler calculations discount viscous effects and are expected to over-predict coherent structures but are able to provide good insight into the phenomenon. Using the approximate incident shock strength, reflection angle, and isentropic exponents of the experiments, the results are displayed in Figure 5.5 which shows the expected reflection behaviour in the (a) hydrogen and (b) methane mixtures. Agreeing with the experimental records, the analogue of the hydrogen-oxygen reflections shows only small vortical structures along the slip-line and very weak forward jetting. In contrast to this, and in agreement with the experiments, the analogue of the methane-oxygen mixtures shows much larger vortical structures and a strong forward jet. This forward jet leads to a large re-circulation zone behind the Mach stem. The

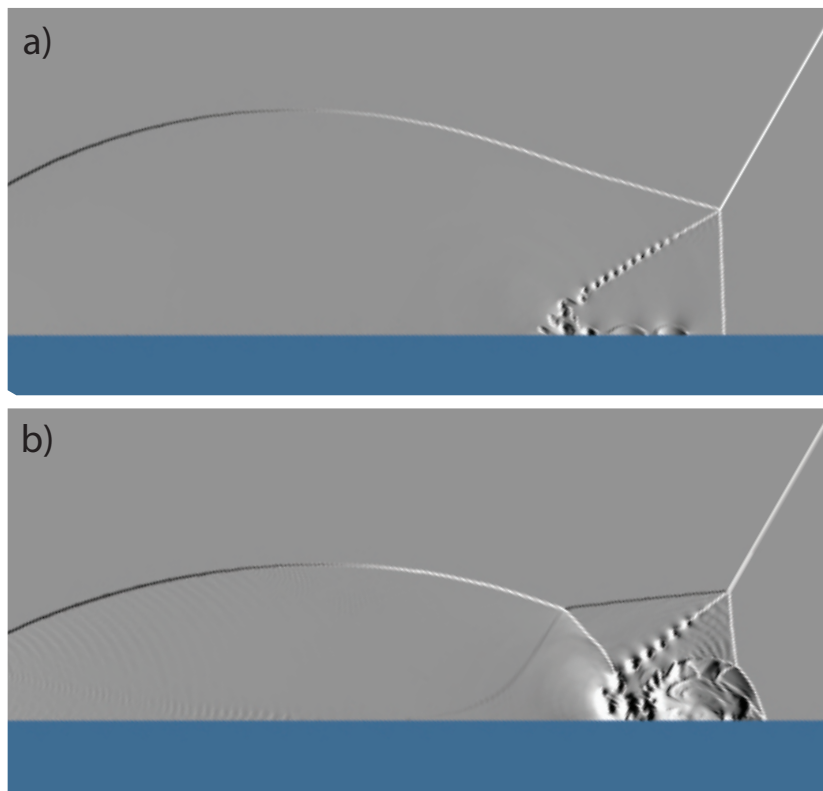


Figure 5.5: Inert shock reflections in modelled Hydrogen-Oxygen and Methane-Oxygen mixtures; the incident shock Mach number is taken as $1/2$ of the CJ velocity for both cases, 30° incidence angle and $\gamma = 1.36$ and 1.2 respectively.

numerical simulations also predict the bifurcation of the Mach stem by the forward jet.

5.1.3 Turbulence in the Forward Jet

We can examine the region behind the Mach stem and estimate the magnitude of turbulence in the region. If there is strong turbulence in this region, it may explain the rapid burning rates seen in the experimental images of the forward jet.

The slip line in methane-oxygen, seen in Figure 5.4, shows an inert shock reflection with large coherent structures along the slip line. These coherent structures resemble the Kelvin-Helmholtz instability along the slip line. The thickness of the slip line (δ) increases along the slip line. Calculating the velocity difference using triple shock theory leads to an estimation of the magnitude of shear across the slip line to be a 512 m/s difference.

Figure 5.3 shows the inert shock reflection in the hydrogen-oxygen mixture. The large coherent structures, seen in methane-oxygen, are not present along the slip line in the hydrogen-oxygen mixture. This typical reflection does not create a strong forward jet as in the methane-oxygen mixture. Again, calculating an estimate for the velocity difference across the slip line results in a shear of 581 m/s. The value estimated for hydrogen-oxygen is essentially the same as the shear estimated for methane-oxygen.

The gases cannot be discriminated based on the magnitude of the shear along the slip line. The Reynolds number of both mixtures can be calculated for the slip line using the Reynolds number for shear layers, defined as,

$$Re_x = \frac{\rho \Delta u L}{\mu} \quad (5.3)$$

where Δu is the velocity difference across the shear layer and L can be the distance along the shear layer (x) or the thickness of the shear layer (δ) [55]. Evaluating the Reynolds number at the half-way point along the slip line, where $L = 0.03m$, we compute a value of $Re_x = 2.2 \times 10^5$ for methane-oxygen and a value of $Re_x = 1.2 \times 10^5$ for hydrogen-oxygen. As Dimotakis shows [56], the transitional Reynolds number for the slip line is $Re_x \approx 1 - 2 \times 10^4$, clearly showing that the slip lines are well within the turbulent regime.

The fundamental difference between these two mixtures, as we have seen above, is the roll-up of the slip line in the forward jet. Hydrogen-oxygen has a turbulent slip line which does not appear to produce a predominant forward jet. Conversely, methane-oxygen shows a turbulent slip line which displays a prominent forward jet causing what appears to be two vortical structures or re-circulation zones behind the Mach stem.

5.1.4 Kolmogorov Scaling

We can use standard Kolmogorov scaling laws to estimate the magnitude of the turbulent scales in the re-circulation zone behind the Mach stem in methane-oxygen. By understanding the turbulent scales involved, we can better understand the mode of combustion in the jet entrainment and re-circulation zone.

The first Kolmogorov hypothesis postulates that, at a sufficiently large Reynolds number, the eddy turnover time, i.e. the relative velocity, is dependent only on the kinetic energy dissipation rate ϵ and kinematic viscosity ν assuming these eddies are in the universal equilibrium range [57]. Using these terms, an estimation can be made for the eddy turnover time.

An order of magnitude relationship exists amongst the turbulent scales where the Kolmogorov scale is denoted by (η) . The macroscopic length scale, or integral length scale, is denoted by l_i . In this case, we will use the spacing of the obstacle as the characteristic length scale. The turbulent velocity scale, denoted by v_i , can be described by an average velocity difference, or the external velocity scale. In this case we will use the velocity difference across the slip line.

The Kolmogorov time scale, $\tau_\kappa(\eta)$, is the characteristic turnover time of the eddies at the Kolmogorov length scale. This characteristic time scale can be defined as $\tau_\kappa = \sqrt{\nu/\epsilon_i}$ according to the Kolmogorov hypothesis. The kinetic energy dissipation rate can be approximated as $\epsilon \simeq v_i^3/l$. This results in a convenient expression describing the characteristic Kolmogorov eddy turnover time as:

$$t_\kappa(\eta) = \sqrt{\nu l_i / v_i^3} \quad (5.4)$$

We will examine the single cylinder experiments for which we have approximated the velocity scale, characteristic shear v_i , seen in Table 5.1. The integral scale can be taken as $l_i \simeq 2.5$ cm, the cylinder spacing or gap size. This is also approximately the same size as the re-circulation zone seen in the experiments, Figure 5.4. The Kolmogorov turnover time in methane-oxygen becomes approximately $t_\eta \simeq 10^{-1} \mu s$.

This approximation shows the eddy turnover time t_η is over four times faster than the characteristic reaction time $t_r = 4.7 \times 10^{-1} \mu s$. The reactions can be convected very quickly around the re-circulation zone, potentially burning as a distributed flame, or well-stirred reactor.

This may explain the jet of combustion seen accelerating into the re-circulation zone in experiments such as Figure 4.17. The rapid combustion of the re-circulation zone could provide more support for the shock dynamics as seen by the secondary shock wave in Figure 5.1(b). These stronger shock reflections could then cause the fast flame to initiate a detonation as seen in Figures 4.39 & 4.39, 4.33 as well as Figures 4.5.

Chapter 6

Conclusion

6.1 Conclusions

The methane-oxygen experiments showed a continuous generation of hot spots. In the near field and the far field, as the fast flame travelled further down the channel and the number of modes reduced, hot spot generation continued. Detonation initiation was observed at various lengths along the channel. As the sensitivity of the gas was lowered, the detonation initiation was observed further from the obstacle until the lower limit was reached and the initial reflection was inert.

Continued hot spot formation was not seen in the hydrogen-oxygen mixture. When hot spots were generated, a limited number of generations were seen and the wave always decayed as an unsupported shock wave with an ever-trailing reaction zone. Detonation initiation further along the channel after the first reflection was not observed.

This study showed examples of fast flames where chemical kinetics were unable to explain the behaviour or the propensity for detonation initiation. It was found that activation energy or the propensity for hot spot formation (χ), were not the controlling parameters of the fast flames. Comparable values of the activation energy and propensity for hot spots (χ) were estimated for both mixtures, however very different behaviours were observed experimentally.

The isentropic exponent has been shown to be a parameter which may be responsible for the different behaviour displayed by both gas mixtures. The lower isentropic exponent has previously been shown to lead to more predominant forward jetting effects. A more predominant forward jet has been seen to display a re-circulation zone behind the Mach stem. This re-circulation zone has displayed a strong propensity for rapid combustion

creating hot spots or keystone structures. Thus, it is postulated that the isentropic exponent is a controlling parameter of the fast flame. The rapid combustion of the forward jet behind the Mach stem is postulated to be the controlling mechanism of the fast flame propagation.

An order of magnitude analysis estimated the magnitude of the turbulence in the re-circulation zone. The analysis showed that the eddies on the Kolmogorov scale had a turnover time in the re-circulation zone faster than the energy deposition time in methane-oxygen. Indicating the possibility of rapid combustion capable of generating pressure waves which would support the shock dynamics of the fast flames.

6.2 Future work

Future work should expand this study to encompass a wider variety of parameters. Different gas mixtures should be used to control for various parameters. Adjusting the blockage ratios would allow a wider range of shock velocities at various sensitivities. A longer channel would allow the observation of a longer length scale. This would also enable the observation of lower pressures, thus lower chemical sensitivities.

This study does not definitively address the question of turbulent combustion in fast flame. Experimental evidence indicates that localized turbulent combustion in the forward jet may play a dominant role in the propagation of the fast flame. However, further work is required to study the nature of combustion in this region, as well as the macroscopic turbulent flame following the lead shock wave.

This work would be augmented through more detailed numerical simulation in order to gain more insight into parameters such as turbulent fluctuation velocities. This would allow a more detailed analysis to be conducted, bringing the results from an order of magnitude to a more precise value. Detailed numerical turbulent modelling would contribute greatly to the understanding of the fast flame.

Bibliography

- [1] P. Mach and M. I. Radulescu, “Mach reflection bifurcations as a mechanism of cell multiplication in gaseous detonations,” *Proceedings of the Combustion Institute*, 2011.
- [2] J. H. S. Lee, *The Detonation Phenomenon*. Cambridge University Press, 2008.
- [3] Nuclear Energy Agency (NEA), 75 - Paris (FR). and OECD Nuclear Energy Agency. Committee on the Safety of Nuclear Installations and Organisation for Economic Co-operation and Development (OECD), 75 - Paris (FR). Committee on the Safety of Nuclear Installations (CSNI). Group of Experts, *Flame Acceleration and Deflagration-to-detonation Transition in Nuclear Safety: State-of-the-art Report*. NEA-CSNI-R-2000-7, NEA, 2000.
- [4] J. H. S. Lee and I. O. Moen, “The mechanisms of transition from deflagration to detonation in vapor cloud explosions,” *Progress in Energy and Combustion Science*, vol. 6, no. 4, pp. 359–389, 1980.
- [5] E. S. Oran and V. N. Gamezo, “Origins of the deflagration-to-detonation transition in gas-phase combustion,” *Combustion and Flame*, vol. 148, p. 447, Jan. 2007.
- [6] J.-S. Grondin and J. H. S. Lee, “Experimental observation of the onset of detonation downstream of a perforated plate,” *Shock Waves*, vol. 20, p. 381386, 2010.
- [7] P. Oppenheim, A. K. Urtiew, “On genesis of gaseous detonation,” *Industrie Chimique Belge-Belgische Chemische Industrie*, p. 171, Sept. 1966.
- [8] T. Hirano, “Behaviour of propagating flames in premixed media,” *Dynamics of Gaseous Combustion*, vol. 151, pp. 3–24, 1993.

- [9] C. Law and C. Sung, “Structure, aerodynamics, and geometry of premixed flamelets,” *Progress in Energy and Combustion Science*, vol. 26, no. 46, pp. 459 – 505, 2000.
- [10] S. Frolov, “Acceleration of the deflagration-to-detonation transition in gases: From shchelkin to our days,” *Combustion, Explosion, and Shock Waves*, vol. 48, no. 3, pp. 258 – 268, 2012.
- [11] M. Fairweather, G. Hargrave, S. Ibrahim, and D. Walker, “Studies of premixed flame propagation in explosion tubes,” *Combustion and Flame*, vol. 116, no. 4, pp. 504 – 518, 1999.
- [12] J. H. S. Lee, “Initiation of gaseous detonation,” *Annual Review of Physical Chemistry*, vol. 28, no. 1, pp. 75–104, 1977.
- [13] G. H. Marksein, “Interactions of flames and flow disturbances,” *Jet Propulsion*, vol. 26, no. 6, pp. 490–492, 1956.
- [14] A. Teodorczyk, J. H. S. Lee, and R. Knystautas, “Propagation mechanism of quasi-detonations,” *Symposium (International) on Combustion*, vol. 22, no. 1, pp. 1723 – 1731, 1989.
- [15] J. H. S. Lee, “Dynamic parameters of gaseous detonations,” *Ann. Rev. Fluid Mech.*, vol. 16, pp. 311–336, 1984.
- [16] G. Ciccarelli, C. Johansen, and M. Kellenberger, “High-speed flames and ddt in very rough-walled channels,” *Combustion and Flame*, vol. 160, no. 1, 2013.
- [17] K. Shchelkin, “Influence of tube roughness on the formation and detonation propagation in gas,” *Journal of Experimental and Theoretical physics*, vol. 10, pp. 823–827, 1940.
- [18] A. Teodorczyk and J. H. S. Lee, “Detonation attenuation by foams and wire meshes lining the walls,” *Shock Waves*, vol. 4, no. 4, pp. 225–236, 1995.
- [19] K. Shchelkin, “Transformation of slow burning into detonation,” tech. rep., DTIC Document, 1960.
- [20] P. Urtiew and A. Oppenheim, “Experimental observations of the transition to detonation in an explosive gas,” *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, pp. 13–28, 1966.

- [21] J. H. S. Lee, R. Knystautas, and N. Yoshikawa, “Photochemical initiation of gaseous detonations,” *Acta Astronautica*, vol. 5, no. 1112, pp. 971 – 982, 1978.
- [22] G. Ciccarelli, C. T. Johansen, and M. Parravani, “The role of shock-flame interactions on flame acceleration in an obstacle laden channel,” *Combustion and Flame*, vol. 157, pp. 2125–2136, NOV 2010.
- [23] M. I. Radulescu, *The propagation and failure mechanism of gaseous detonations: experiments in porous-walled tubes*. PhD thesis, McGill University, 2003.
- [24] G. Thomas, R. Bambrey, and C. Brown, “Experimental observations of flame acceleration and transition to detonation following shock-flame interaction,” *Combustion Theory and Modelling*, vol. 5, no. 4, pp. 573–594, 2001.
- [25] S. Ohyagi, T. Obara, S. Hoshi, P. Cai, and T. Yoshihashi, “Diffraction and re-initiation of detonations behind a backward-facing step,” *Shock Waves*, vol. 12, no. 3, pp. 221–226, 2002.
- [26] D. R. White and K. H. Cary, “Structure of gaseous detonation. ii. generation of laminar detonation,” *The Physics of Fluids*, vol. 6, p. 749, 1963.
- [27] D. H. Edwards, G. Hooper, and G. O. Thomas, “Two-dimensional nozzle-generated reactive blast wave,” *Journal of Physics D: Applied Physics*, vol. 833, p. 40, 1981.
- [28] T. Obara, J. Sentanuhady, Y. Tsukada, and S. Ohyagi, “Reinitiation process of detonation wave behind a slit-plate,” *Shock Waves*, vol. 18, no. 2, pp. 117–127, 2008.
- [29] J. C. Chao, *Critical deflagration waves that lead to the onset of detonation*. PhD thesis, McGill University, 2006.
- [30] M. I. Radulescu and B. M. Maxwell, “The mechanism of detonation attenuation by a porous medium and its subsequent re-initiation,” *Journal of Fluid Mechanics*, vol. 667, pp. 96–134, 2011.
- [31] R. Bhattacharjee, S. Lau-Chapdelaine, G. Maines, L. Maley, and M. Radulescu, “Detonation re-initiation mechanism following the mach reflection of a quenched detonation,” *Proceedings of the Combustion Institute*, vol. 34, pp. 1893–1901, 2013.

- [32] R. Bhattacharjee, S. Lau-Chapdelaine, G. Maines, L. Maley, and M. Radulescu, “Detonation re-initiation mechanism following the mach reflection of a quenched detonation,” *Proceedings of the Combustion Institute*, vol. 34, no. 2, pp. 1893 – 1901, 2013.
- [33] R. Sorin, R. Zitoun, B. Khasainov, and D. Desbordes, “Detonation diffraction through different geometries,” *Shock Waves*, vol. 19, no. 1, pp. 11–23, 2009.
- [34] R. Knystautas, J. H. S. Lee, and C. M. Guirao, “The critical tube diameter for detonation failure in hydrocarbon-air mixtures,” *Combustion and Flame*, vol. 48, pp. 63–83, 1982.
- [35] G. Settles, *Schlieren and Shadowgraph Techniques*. Springer, 2001.
- [36] M. J. Hargather and G. S. Settles, “Retroreflective shadowgraph technique for large-scale flow visualization,” *Applied Optics*, vol. 48, no. 22, pp. 4449–4457, 2009.
- [37] K. Dennis, L. Maley, Z. Liang, and M. I. Radulescu, “Implementation of large scale shadowgraphy in hydrogen explosion phenomena,” *International Journal of Hydrogen Energy*, vol. 39, pp. 11346–11353, JUL 15 2014.
- [38] M. Kaneshige and J. E. Shepherd, “Detonation database,” Tech. Rep. FM97-8, GALCIT, July 1997. See also the electronic hypertext version at http://www.galcit.caltech.edu/detn_db/html/.
- [39] S. Gordon and B. McBride, “Computer program for calculation of complex chemical equilibrium compositions and applications,” tech. rep., National Aeronautics Space Administration, 1994.
- [40] D. Goodwin, *Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics and transport processes*. available from <http://code.google.com/p/cantera/>, 2009.
- [41] G. Smith, D. M. Golden, M. Frenklach, N. Moriarty, B. Eiteneer, M. Goldenberg, C. Bowman, R. Hanson, S. Song, G. W.C.Jr., V. Lissianski, and Z. Qin, “Gri-mech 3.0,” tech. rep., Berkeley, 2002. http://www.me.berkeley.edu/gri_mech/.
- [42] J. Li, Z. Zhao, A. Kazakov, and F. L. Dryer, “An updated comprehensive kinetic model of hydrogen combustion,” *International Journal of Chemical Kinetics*, vol. 36, no. 10, pp. 566–575, 2004.

- [43] C. Law, *Combustion Physics*. Cambridge University Press, 2006.
- [44] G. Ben-Dor, *Shock Wave and High Pressure Phenomena*. Springer, 2007.
- [45] M. S. Kuznetsov, V. I. Alekseev, and S. B. Dorofeev, “Comparison of critical conditions for ddt in regular and irregular cellular detonation systems,” *Shock Waves*, vol. 10, no. 3, pp. 217–223, 2000.
- [46] M. Radulescu, G. Sharpe, and D. Bradley, “A universal parameter quantifying explosion hazards, detonability and hot spot formation, the χ number,” in *Proceedings of the Seventh International Seminar on Fire & Explosion Hazards* (D. Bradley, G. Makhviladze, V. Molkov, P. Sunderland, and F. Tamanini, eds.), pp. 617–626, University of Maryland, Research Publishing, 2013.
- [47] Z. Liang, S. Browne, R. Deiterding, and J. E. Shepherd, “Detonation front structure and the competition for radicals,” *Proceedings of the Combustion Institute*, vol. 31, pp. 2445–2453, 2007.
- [48] D. Bradley, “Autoignitions and detonations in engines and ducts,” *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, vol. 370, no. 1960, pp. 689–714, 2012.
- [49] H. Hornung, “Regular and mach reflection of shock waves,” *Annual Review of Fluid Mechanics*, vol. 18, no. 1, pp. 33–58, 1986.
- [50] L. F. Henderson, E. I. Vasilev, G. Ben-Dor, and T. Elperin, “The wall-jetting effect in mach reflection: theoretical consideration and numerical investigation,” *Journal of Fluid Mechanics*, vol. 479, pp. 259–286, 3 2003.
- [51] A. Semenov, M. Berezkina, and I. Krasovskaya, “Classification of shock wave reflections from a wedge. part 2: Experimental and numerical simulations of different types of mach reflections,” *Technical Physics*, vol. 54, no. 4, pp. 497–503, 2009.
- [52] S. S.-M. Lau-Chapdelaine, “Numerical simulations of detonation re-initiation behind an obstacle,” Master’s thesis, University of Ottawa, 2013.
- [53] L. Maley, R. Bhattacharjee, S. S.-M. Lau-Chapdelaine, and M. I. Radulescu, “Influence of hydrodynamic instabilities on the propagation mechanism of fast flames,” in *Proceeding of the Combustion Institute*, 2014.

- [54] J. J. Quirk, “Amrita.” VKI 29th CFD lecture series,, Febuary 1998.
- [55] C. L. Bond, *Reynolds Number Effects on Mixing in the Turbulent Shear Layer*. PhD thesis, California Institute of Technology, 1999.
- [56] P. E. Dimotakis, “Turbulent mixing,” *Annual Review of Fluid Mechanics*, vol. 37, pp. 329–356, 2005.
- [57] S. Tavoularis, *Theory of Turbulence: Lecture Notes*. University of Ottawa, 2012.
- [58] J. M. Austin, *The Role of Instability in Gaseous Detonation*. PhD thesis, California Institute of Technology, 2003.

Appendix A

Interpreting Experimental Images

A.1 Reading the Schlieren and Shadowgraph Images

This study has focused on visualization of the quazi-two dimensional shock flame complexes using schlieren and shadowgraph images. These optical techniques rely on changes in the density gradient (hence changes in the refractive index) to visualize the structures. This permits direct visualization of the structures of interest, shock waves, reaction zones, etc. due to the change in density across these structures. The Schlieren imaging visualizes the first density gradient, the change in density; where the shadowgraph imaging visualizes the second density gradient, the change in the change of density.

From the images showing the density gradients much understanding can be gained through the interpretation of the images. In the context of shock and detonation research much work has been done in the past which is here built on to gain this understanding. Sharp density jumps are direct observations of shock waves. These are seen as strong lines on the images, since from basic shock wave theory (shock jump equations) we know that the shock wave is defined as a sudden jump in pressure and density.

We can also interpret these images to gain an understanding of the combustion processes from interpretations of the images. Combustion theory tells that across a combustion reaction the gas undergoes a density change. These reaction zones are thin compared with the length scales in the experiment, hence the reaction zones appear as lines on the images.

To ensure these interpretations are correct researchers have conducted simultaneous density gradient and chemical kinetic visualizations [58]. Seen in Figure A.1 is a simultaneous Schlieren image, an OH* luminescence image, and the false colour OH*

luminescence image overlaid on an enlarged area of the Schlieren image. The OH* luminescence shows where the most intense regions of combustion are occurring. This examples illustrates a similar structure to those seen in this study, where the lead shock does not immediately induce any chemical activity, but after a delay period, a second density change is seen in the Schlieren image, using the OH* luminescence image we can see that this second density change corresponded to the combustion zone. These types of images help the interpretation of the density gradient images used in this study. The equipment to produce the simultaneous Schlieren and OH* luminescence images was unavailable for this study.

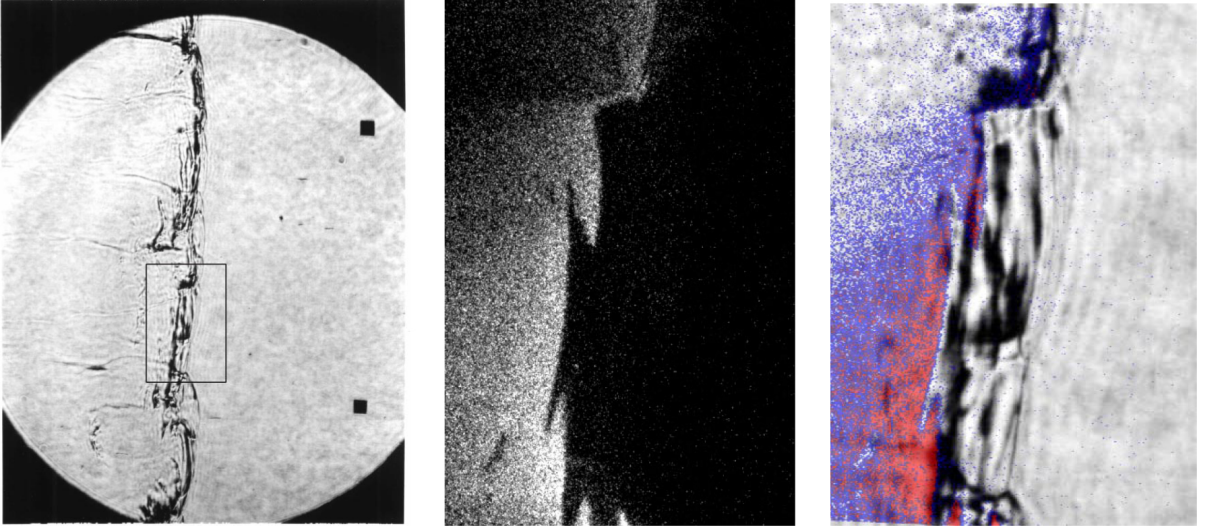


Figure A.1: Simultaneous schlieren and OH* image by J. Austin at Caltech, Shot 157: 2H₂-O₂-3.5N₂ $P_0 = 21$ kPa

A.2 Pre-compression in the tube

Many combustion experiments involving fluid flow include a fluid pre-compression and therefore the entire length of the channel does not have the same initial conditions. Pre-compression in these experiments is not a problem as the detonations and lead shock waves are supersonic, therefore the information of the oncoming waves is unable to propagate forward ahead of the lead shock.

The end of the window section does not represent the end of the tube, the end of the tube is a plate approximately three inches past the end of the window section. For this

reason shock reflections against the upper and lower walls as the wave disappears behind the window frame are still valid and do not include a normal shock reflection.

Appendix B

Image Adjustments

The images that have been shown here have been adjusted. There have been a variety of basic manipulations commonly done to all of the image adjusting the grey scale, brightness and contrast. These basic manipulations help the reader interpret the images but do not change the image, they just adjust the signal strength of the colours.

A comparison of the raw images to those adjusted is seen in Figure B.1.

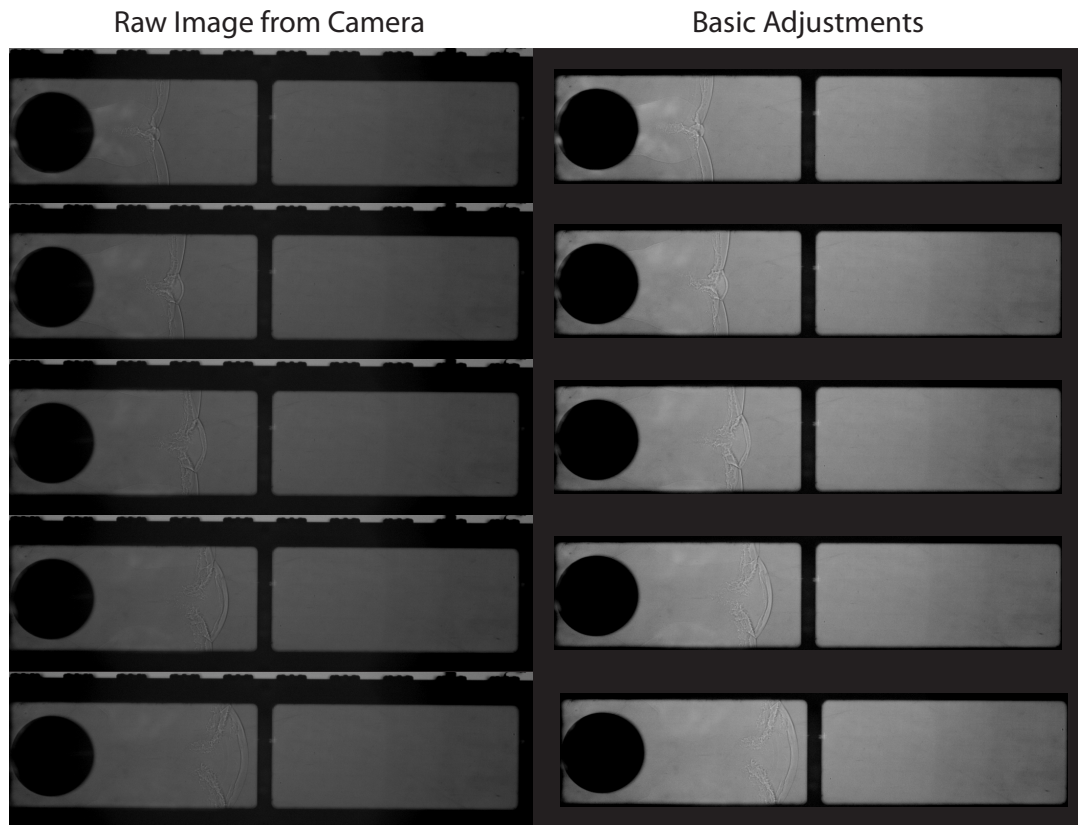


Figure B.1: Comparison of basic tone adjustments

The more in-depth adjustment that has been made to the images is the background subtraction. This technique involves the use of the first image in the series, before the wave has entered the frame. Using this reference image, all pixels are compared and the value of the reference image is subtracted if they are different. The program used for this operation was developed by Shem Lau-Chapdelaine at the University of Ottawa.

The adjustments made have been done post analysis to allow an easier understanding and interpretation. As seen here in figure B.2 is a direct comparison between a simple contrast, brightness, grey scale adjustment, and a background subtraction image.

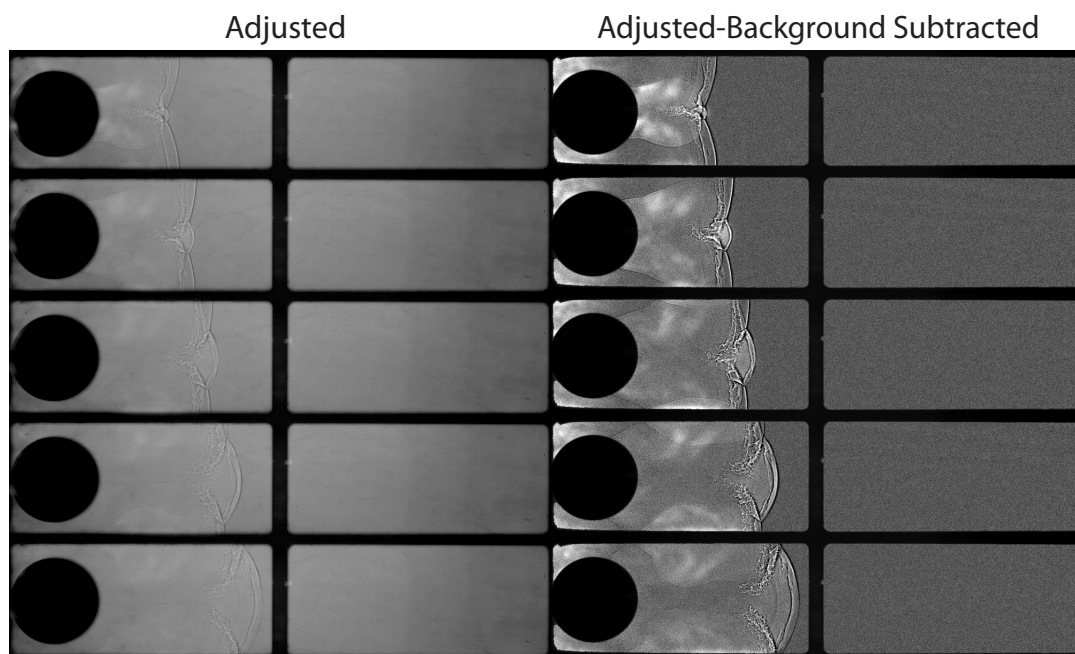


Figure B.2: Comparison of the adjustments and background subtraction

Appendix C

The High Voltage Igniter (HIV)

The ignition source used in this study was the a capacitive discharge using a custom made spark plug. The igniter was designed in and made in McGill university by Sev Kamenskih. An image of the HVI before installation is seen in Figure C.1, curtsey of S. Kamenskih. The material in this section is a reproduction of the original documentation of the high voltage igniter.

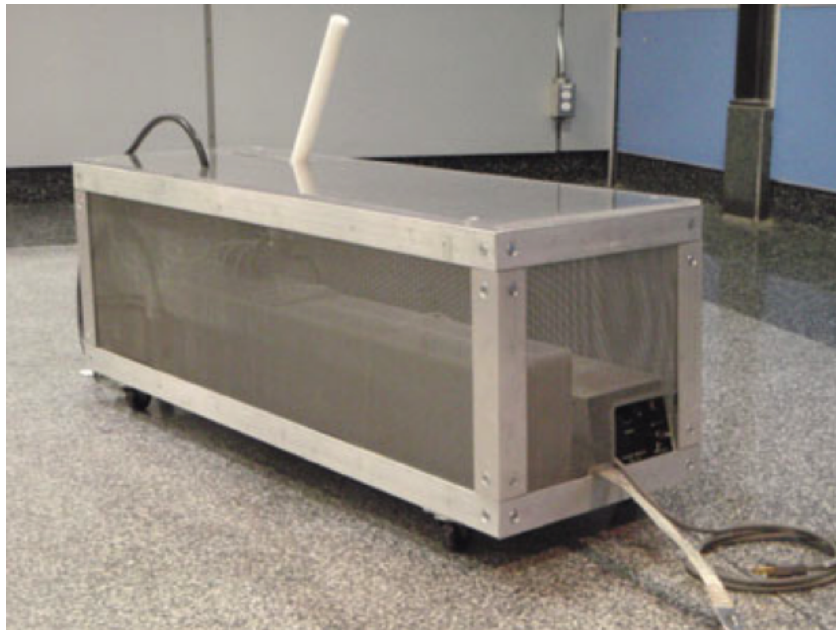


Figure C.1: Image of the High Voltage Igniter (HVI), curtsey of S. Kamenskih

This ignition system is capable of storing upto 1 kilojoule of energy in the two parallel plate capacitors and releases the energy in a short duration high current pulse, 35 000A

in $2 \mu s$. The system is triggered by a TTL signal to a TM-11A trigger module which releases the capacitors (2 General Atomics capacitors # 31158) energy using a Perkin Elmer GP-41B spark gap as seen in Figure C.2.

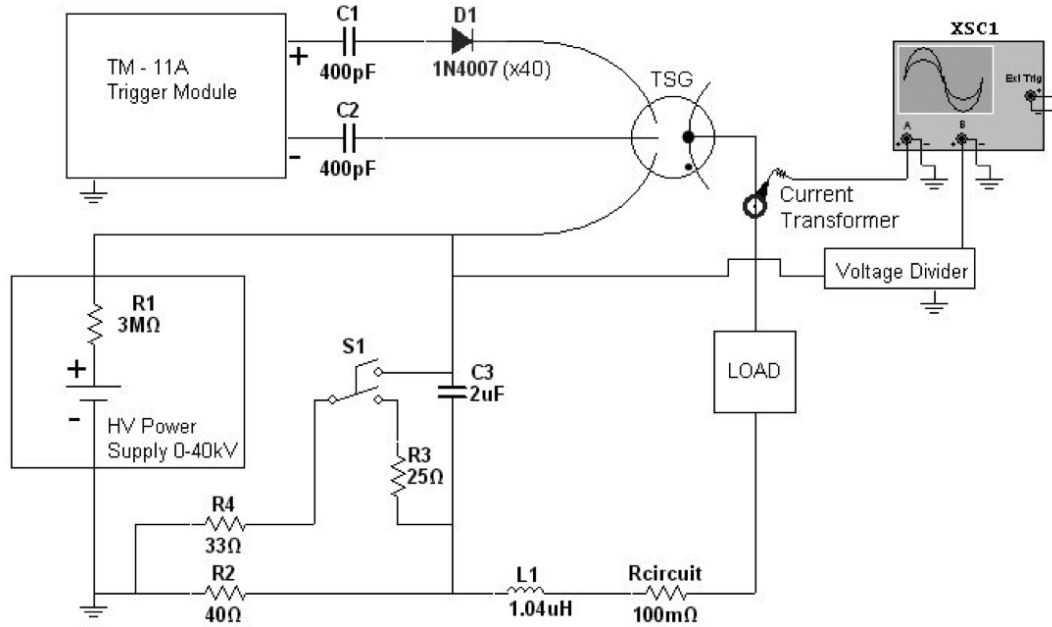


Figure C.2: Circuit diagram of the High Voltage Igniter (HVI)

The specific details of the igniter can be found in Table C as described by the manufacturer. For safety purposes the HVI was manufactured with a founded steel cage as well as a safe discharge switch which protrudes from the unit.

Testing was conducted in McGill before the unit was at the university of Ottawa. This testing was conducted to characterise the performance of the unit, to do the testing a CT-1025 current transformer for the current measurements and a VD-305A voltage divider for simultaneous measurement of the capacitor voltage. The lead used for this testing was a 4mm spark gap in open air, thus in the circuit diagram (Figure C.2) can be replaced with a spark resistance of 0.01-0.03 Ohm. The $R_{circuit}$ is the total circuit resistance resulting from resistance of the connecting wires, triggered spark gap (TSG) and capacitor plates and $L1$ is the parasitic inductance of the circuit.

Diagrams shown here are a subset of the tests done reproduced from the original manufacturer's report. The experiments conducted in this work were done using a capacitor voltage between 20 and 25-kV, Figure C.3 and C.4 show the current and voltage

Table C.1: Specifications of the High Voltage Igniter (HVI)

Specifications	
Electrical Input	
Voltage	0-32kVDC
Current	0.5-2.5mA
Power	80W
Electrical Output	
Voltage Range	15-32kV (based on use with GP-41B spark gap)
Peak Current	35,000A (@ Vinitial = 30kV)
Stored Energy	up to 1000J (0.5CV ² @ 32kV)
Pulse width	>3.5s (@ 1/3 of peak amplitude)
Rise Time	Less than 2s (measured from 10% to 90% points on leading edge of output pulse)
Mechanical	
Input Cable	RG 8/U (for charging), Standard 110/230 VAC, 50/60Hz 3 wire cord (for TM-11A trigger)
Output Cable	RG 8/U
External Trigger	BNC jack
Remote Trigger	Jones plug receptacle
Ground Connection	Braided grounding cable 4 gauge with 5/8 lug end
Controls	Off-On Safe Discharge Lever, Off-On trigger push button
Size	12 in. x 36 in. x 14 in
Weight	70 lb

waveforms of a discharge conducted at these voltages.

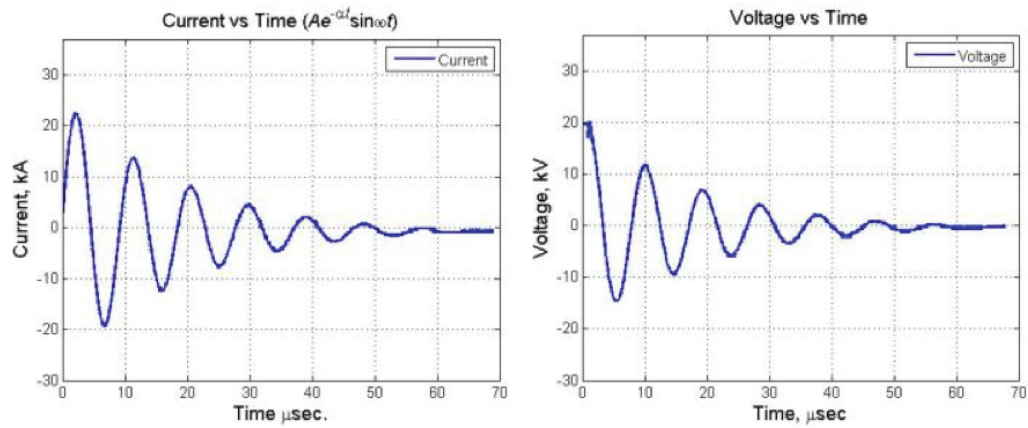


Figure C.3: Waveform, current and voltage, results tested under $V_0 = 20\text{kV}$

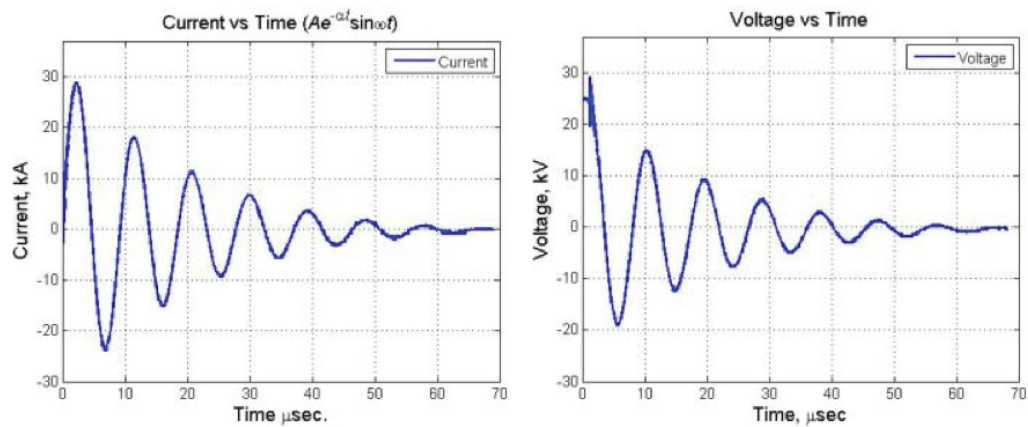


Figure C.4: Waveform, current and voltage, results tested under $V_0 = 25\text{kV}$

The energy release by the Igniter was estimated by the manufacturer and is attached here below.

Spark Energy

ENERGY ESTIMATION FROM HIGH-VOLTAGE CAPACITOR DISCHARGE [1]

As seen in the ignition circuit diagram (Figure 1) the energy deposited inside the sphere comes from the discharge of the high voltage capacitor bank. Total energy stored in the capacitors ($E_T = CV^2/2$) could be used to estimate the energy required to detonate a combustible mixture. However this estimate will only give the order of magnitude approximation to the actual energy deposited in the sphere since it does not take into account energy loss in circuit components and loss via ohmic dissipation. The actual energy deposited inside the mixture is found by integrating the square of current function $i(t)^2$

multiplied by the spark resistance (R_s): $E_s = \int i^2 R_s dt$. The ignition circuit in Figure 1 can be simplified to an equivalent RLC circuit shown in Figure 2.

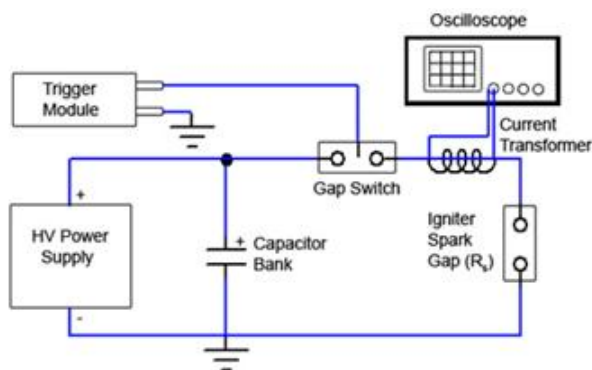


Figure 1. Ignition Circuit Components Diagram

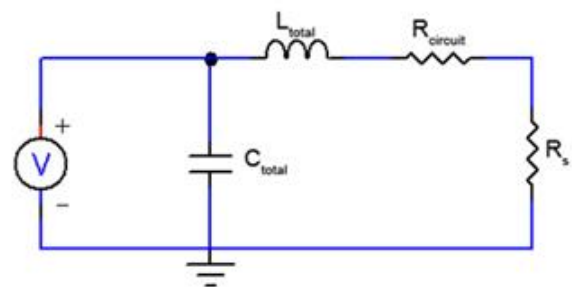


Figure 2. Equivalent RLC Circuit

Thus for a damped oscillatory discharge the current can be described as: $i(t) = Ae^{-\alpha t} \sin(\omega t)$. Attenuation factor is equal to $\alpha = R_{total}/2L_{total}$ and frequency of the discharge is equal to $\omega = \sqrt{1/(LC)_{total} - (R/2L)_{total}^2} = \omega_n \sqrt{1 - \zeta^2}$, where ω_n is the natural frequency of the undamped

discharge and ζ is the damping factor. The total circuit resistance ($R_{\text{total}} = R_{\text{circuit}} + R_s$) is a combination of the resistance of all the circuit components R_{circuit} and igniter spark gap resistance R_s . To estimate the energy E_s deposited into the mixture from a trace of the current function on the oscilloscope, the following procedure is outlined:

1. Natural frequency ω_n is determined using ω and ζ found from the current trace.
2. Total circuit inductance is found from $L_{\text{total}} = 1/\omega_n^2 C_{\text{total}}$
3. Total circuit resistance is found as follows $R_{\text{total}} = 2L_{\text{total}}\alpha$
4. Spark Resistance R_s is determined by subtracting $R_{\text{total}} = R_{\text{circuit}}$ when the spark gap is shorted out $R_s \approx 0$ from $R_{\text{total}} = R_{\text{circuit}} + R_s$ when the spark is not shorted. Current traces of the two cases are shown in Figure 3 for capacitor initial voltage of 20kV.
5. Total Energy deposited into the mixture is found by numerically integrating the square of

the current multiplied by spark resistance $E_s = \int i^2 R_s dt$.

It should be noted that according to Lee et al. only the energy deposited in the first $\frac{1}{4}$ of the discharge cycle is responsible for detonating the mixture. Thus the test results summarized in Table 1 include both the total energy and energy deposited in the first $\frac{1}{4}$ cycle.

Table 1. Discharge Characteristics

$E_{\text{initial}}(\text{J})$	V_0 (kV)	$C_{\text{disch}}(\mu\text{F})$	$L_{\text{disch}}(\mu\text{H})$	$R_{\text{disch}}(\Omega)$	Spark			
					$R_{\text{spark}}(\Omega)$	$E_{1/4 \text{ cycle}}(\text{J})$	$E_{\text{convert}}(\text{J})$	$E_{\text{total}}(\text{J})$
400.0	20	2	1.04	0.096	0.011	5.426	5.375	32.2343
625.0	25	2	1.04	0.095	0.0095	8.3326	8.2951	54.1889
900.0	30	2	1.04	0.096	0.0079	11.2182	10.982	61.585

The shorted and open current waveforms are shown below for initial voltages of 20kV, 25kV and 30kV:

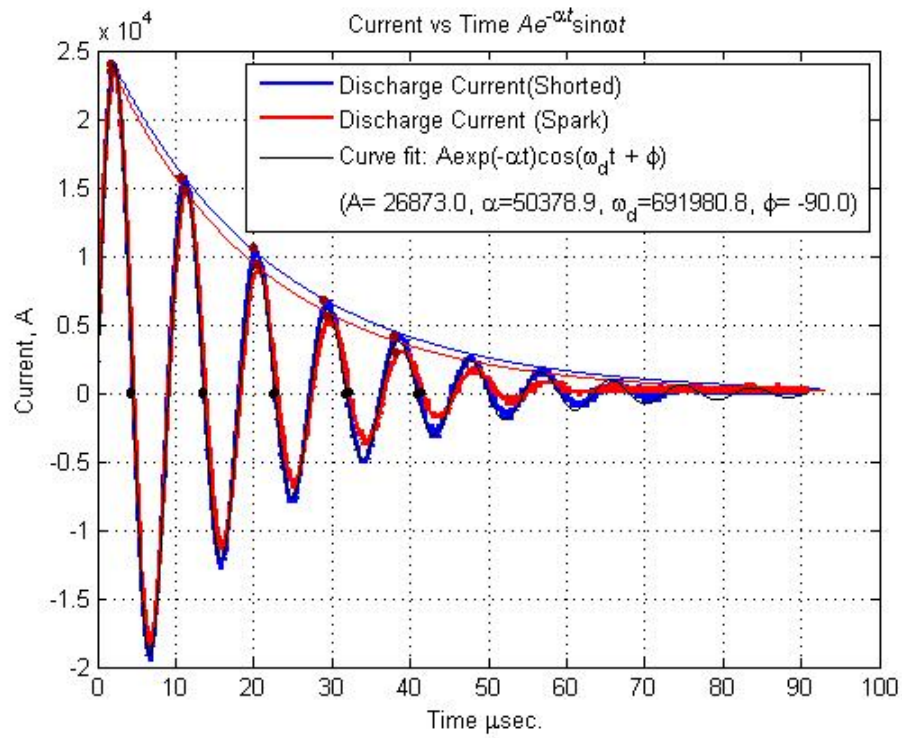


Figure 3. Current Waveform – shorted and open spark gap ($V_0 = 20\text{kV}$)

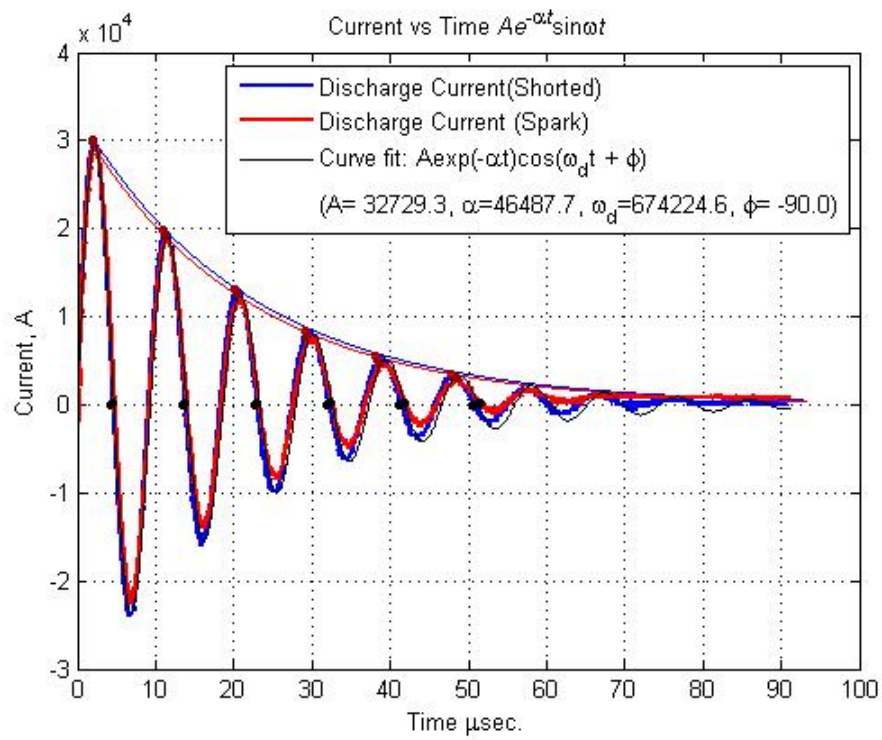


Figure 4. Current Waveform – shorted and open spark gap ($V_o = 25\text{kV}$)

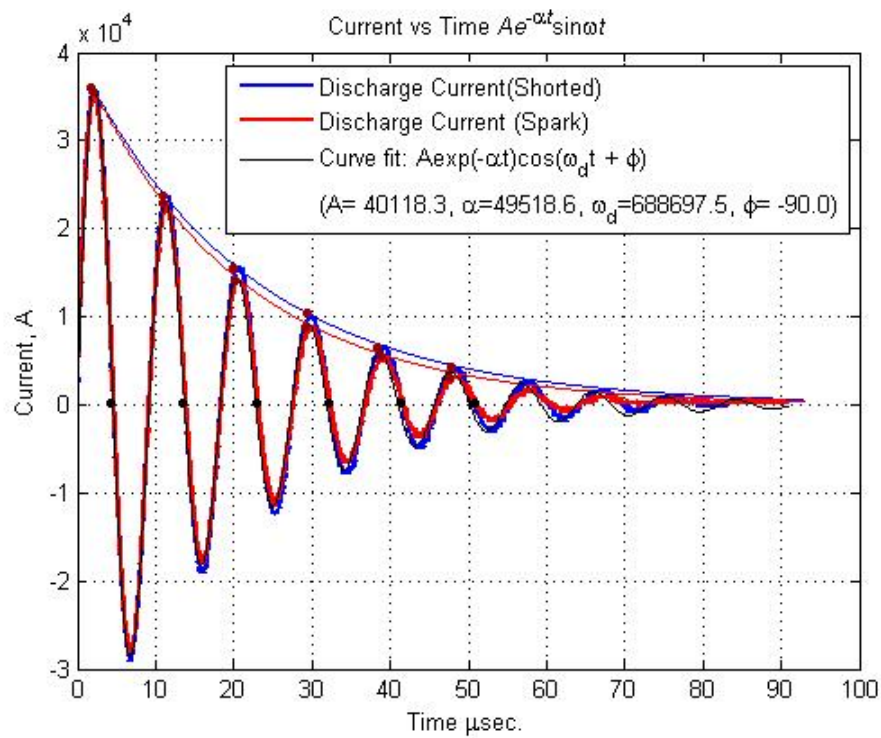


Figure 5. Current Waveform – shorted and open spark gap ($V_o = 30\text{kV}$)

As seen from Table 1 the spark resistance is small. Increasing the distance between the electrodes or using an exploding wire will increase the resistance of the spark gap and thus increase the energy deposited in the spark gap.

References

- [1] Kamenskihs, V., Ng, H.D. and Lee, J.H.S. (2010) Measurement of critical energy for direct initiation of spherical detonations in high-pressure $\text{H}_2\text{-O}_2$ mixtures. Combustion and Flame, (CNF-D-09-00384)

[2] Knystautas, R. and Lee, J.H.S. (1976) On the effective energy for direct initiation of gaseous detonations. *Combust. Flames* 27: 221-228.

[3] Zhukov, V.P., Rakitin, A.E. and Starikovskii, A.Yu. (2008) Effect of High-Voltage Pulsed Discharges on Deflagration to Detonation Transition. *J. Prop. Power* 24: 88-93.

Appendix D

Image Velocimetry Uncertainty Calculations

To calculate the error of the velocity calculated from these high speed images standard error propagation was used, calculated using the uncertainty in time and the uncertainty of space. The uncertainty in time is defined as the uncertainty of the shutter closing. In space the uncertainty is defined as the width of one pixel represents in the image.

As the velocity being measured is only in the x-direction and the detonation continues to move forward the time the shutter is open becomes irrelevant and the uncertainty is reduced to uncertainty in time it takes to close the electronic shutter. The time difference between both frames is defined as the inter-frame time and the exposure time.

To calculate the uncertainty in space, a known distance in each series of images and the number of pixels is used. This defines the repetitiveness size of each pixel. When analysing the images it is assumed that the position of the lead shock can be located to within one pixel.

The uncertainty in the velocity is calculated by the the error propagation of these uncertainties.

$$\delta V = V \left(\left(\frac{x_{\text{uncertainty}}}{\Delta x} \right)^2 + \left(\frac{t_{\text{uncertainty}}}{\Delta t} \right)^2 \right)^{1/2} \quad (\text{D.1})$$

Appendix E

Hydrogen-Oxygen Experiments

The full experimental records for the experiments discussed above, unless shown above.

E.1 Five Cylinder Experiments

E.1.1 Shadowgraph Images

Hydrogen-Oxygen Five Cylinder 18.6 kPa Shadowgraph

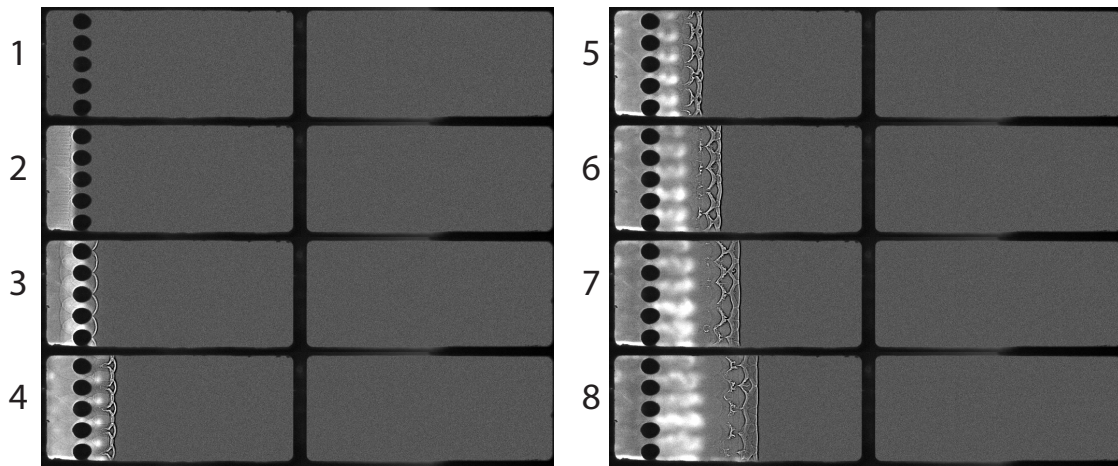


Figure E.1: Part A of full shadowgraph record of images illustrating the detonation failure at the maximum pressure tested in $2\text{H}_2\text{-O}_2$, $p_0 = 18.6\text{kPa}$. Recorded at $21.72 \mu\text{s}$ interframe time, $1\mu\text{s}$ exposure, 46040.5 fps

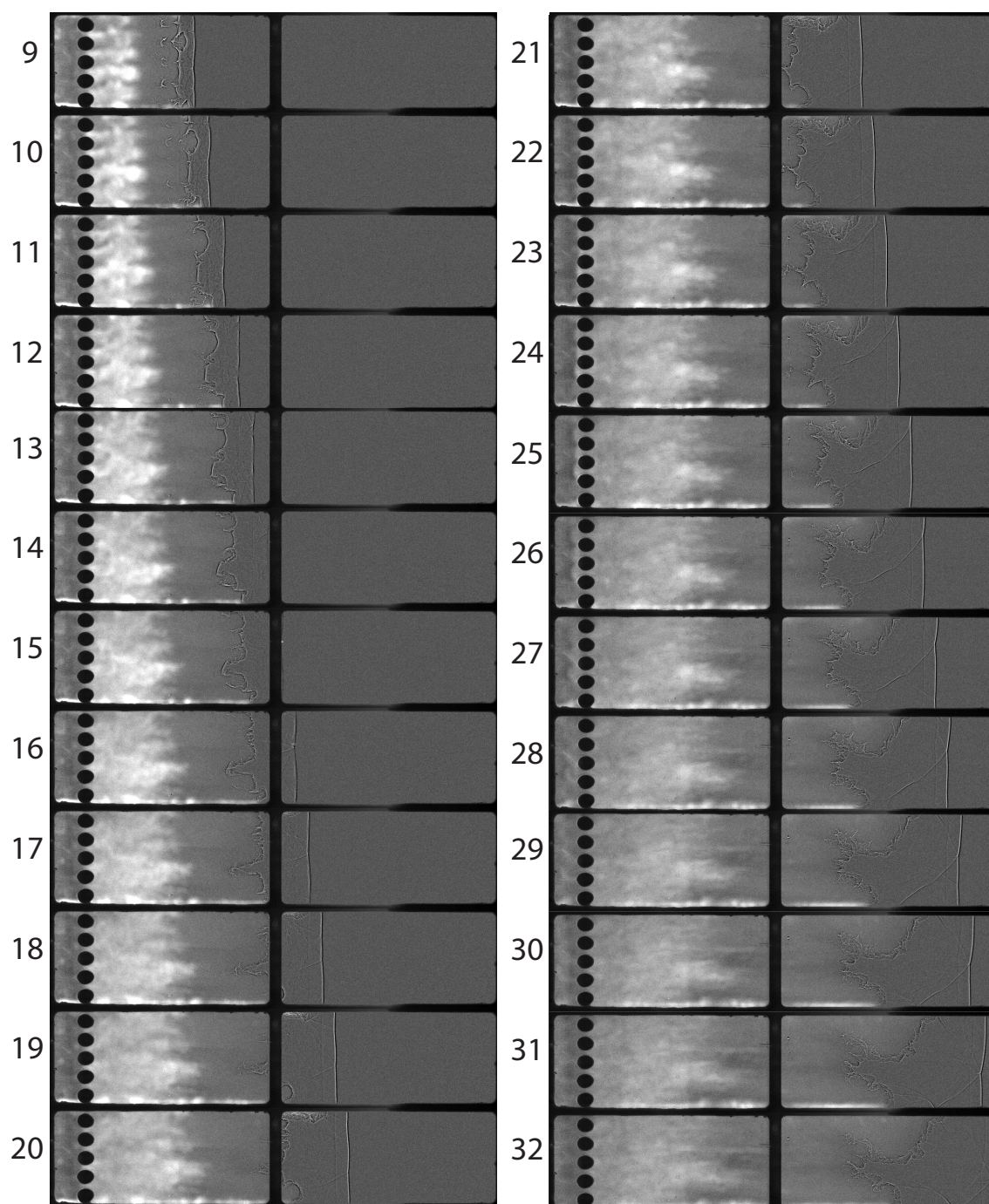


Figure E.2: Part B of full shadowgraph record of images illustrating the detonation failure at the maximum pressure tested in $2\text{H}_2\text{-O}_2$, $p_0 = 18.6\text{kPa}$. Recorded at $21.72\ \mu\text{s}$ interframe time, $1\ \mu\text{s}$ exposure, 46040.5 fps

Hydrogen-Oxygen Five Cylinder 17.2 kPa Shadowgraph

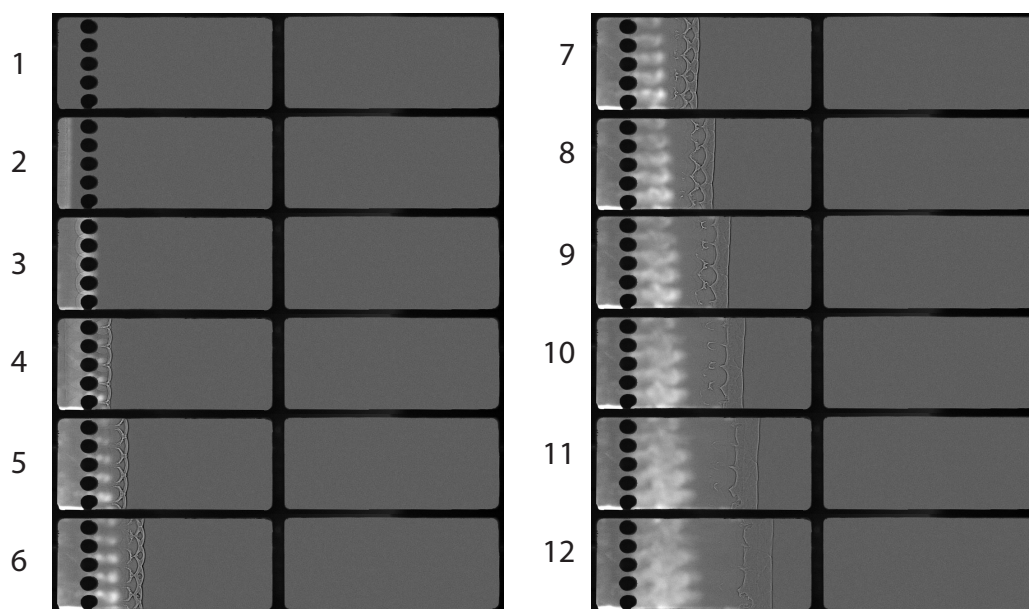


Figure E.3: Part A of full shadowgraph record of images illustrating the decay of the fast flame in $2\text{H}_2\text{-O}_2$, $p_0 = 17.2\text{kPa}$. Recorded at $21.72 \mu\text{s}$ interframe time, $1\mu\text{s}$ exposure, 46040.5 fps

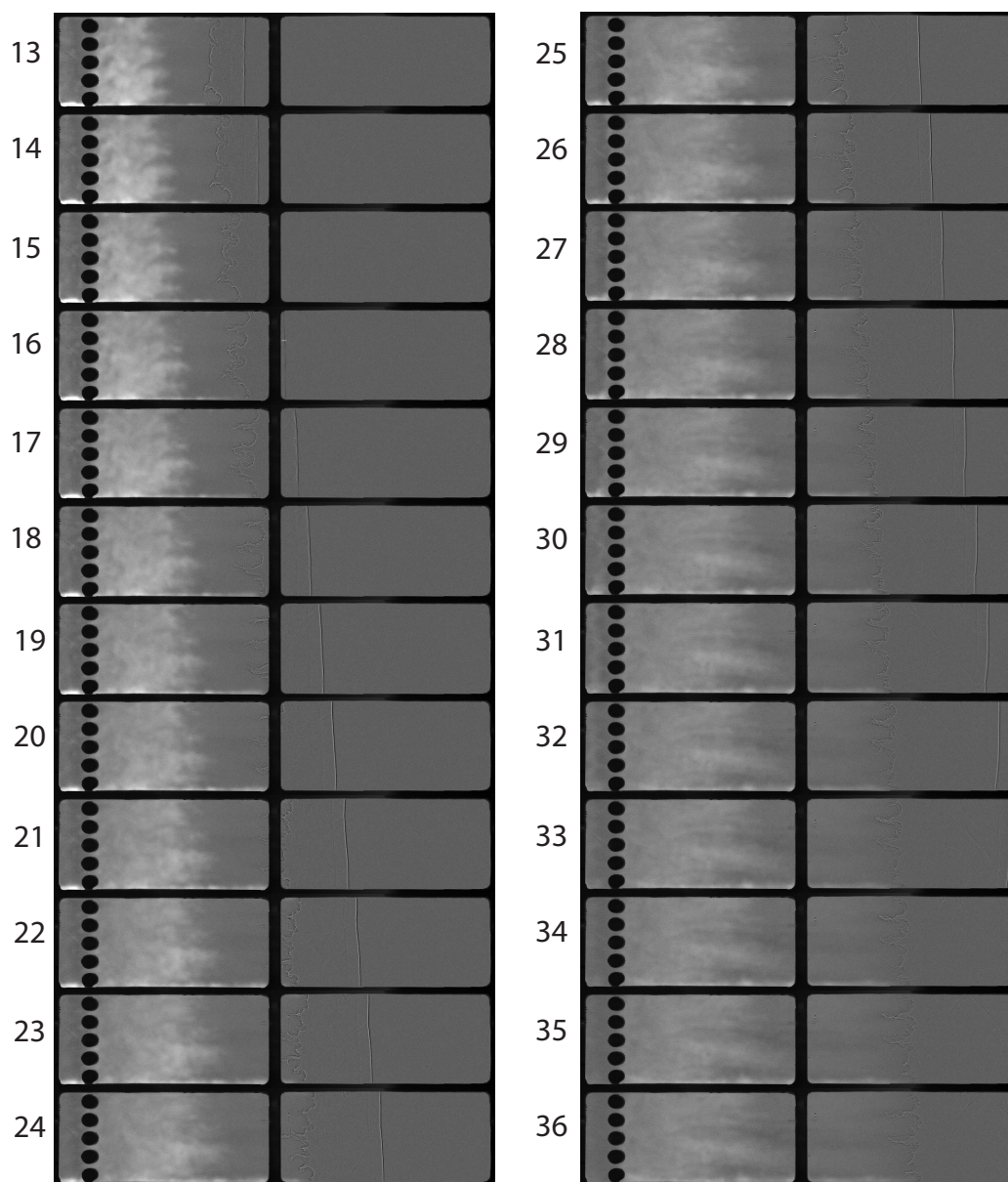


Figure E.4: Part B of full shadowgraph record of images illustrating the decay of the fast flame in $2\text{H}_2\text{-O}_2$, $p_0 = 17.2\text{kPa}$. Recorded at $21.72 \mu\text{s}$ interframe time, $1\mu\text{s}$ exposure, 46040.5 fps

E.2 Single Cylinder Experiments

E.2.1 Shadowgraph Images

Hydrogen-Oxygen Single Cylinder 14.2 kPa Shadowgraph

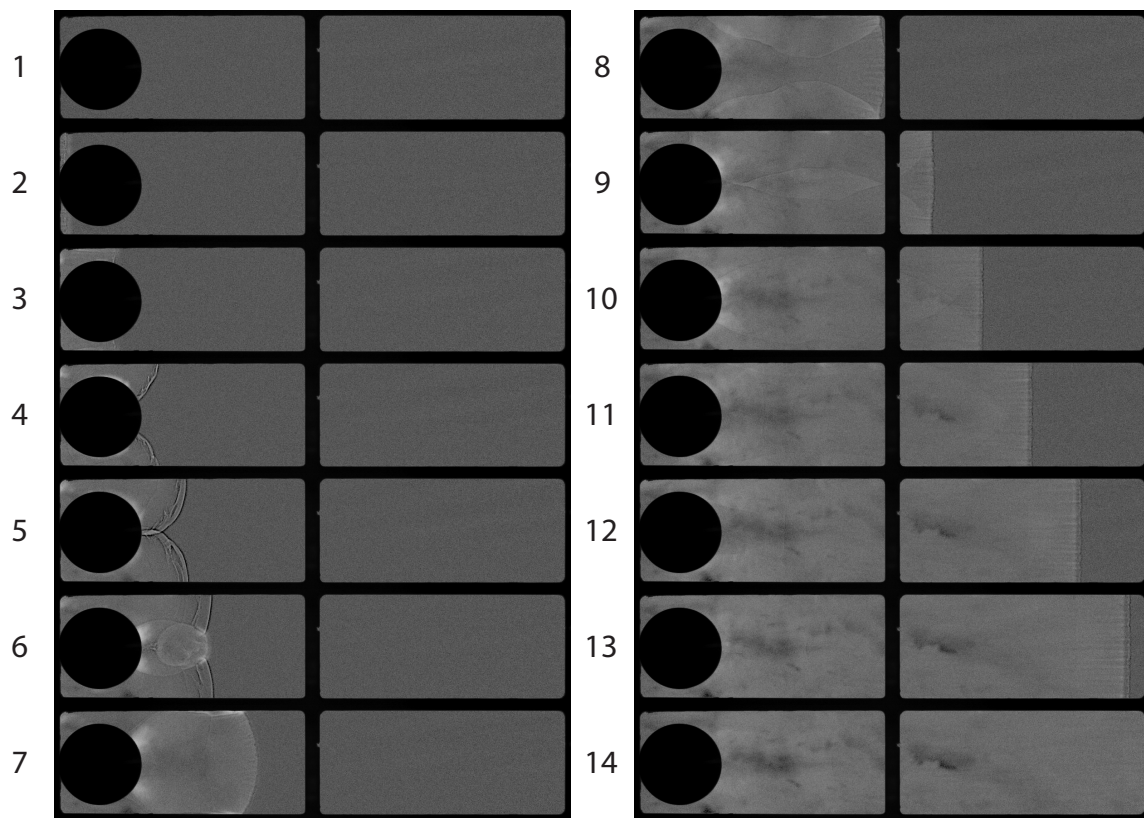


Figure E.5: Full record of shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder and subsequent detonation initiation upon reflection. $p_0 = 14.2\text{kPa}$. Recorded at $21.72\ \mu\text{s}$ interframe time, $4.78\ \mu\text{s}$ exposure, 46040.51fps.

Hydrogen-Oxygen Single Cylinder 13.8 kPa Shadowgraph

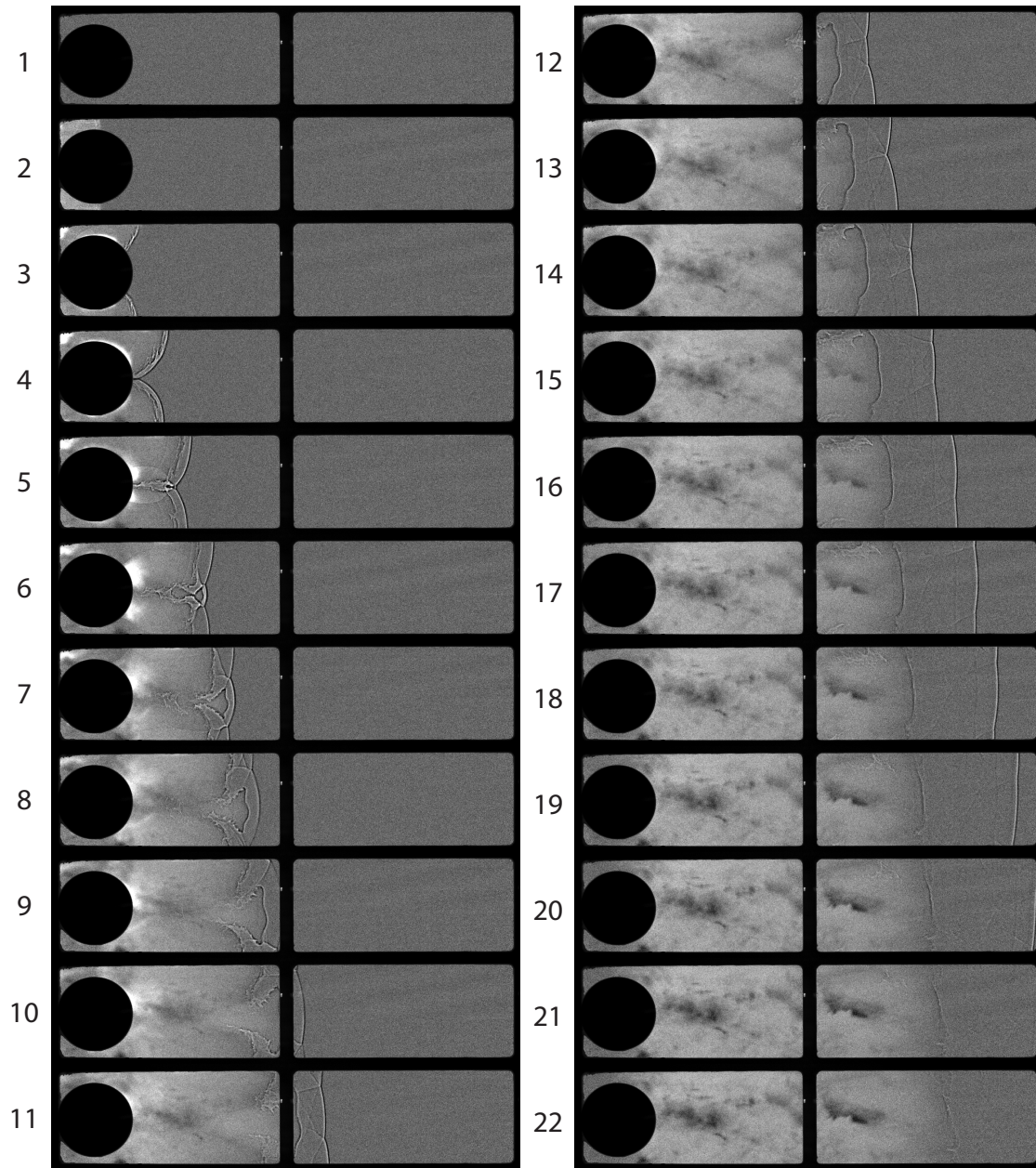


Figure E.6: Full record of shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder, reactive reflection and subsequent wave decay at $p_0 = 13.8$ kPa. Recorded at $21.72 \mu s$ interframe time, $4.78 \mu s$ exposure, 46040.51fps.

Hydrogen-Oxygen Single Cylinder 8.6 kPa Shadowgraph

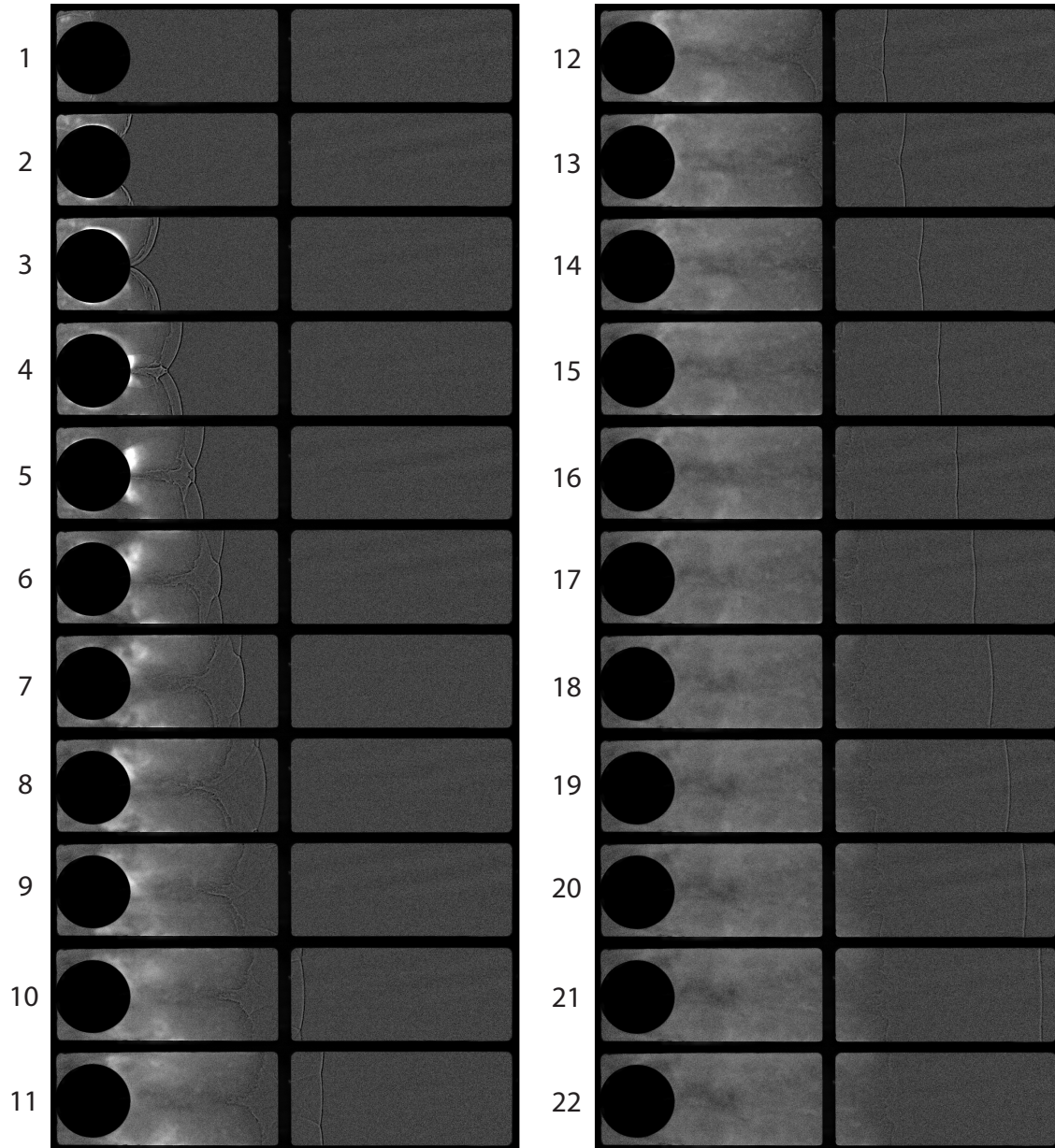


Figure E.7: Shadowgraph record of hydrogen-oxygen, $p_0 = 8.6\text{kPa}$, detonation failure around the single cylinder and subsequent wave decay

E.2.2 Schlieren Images

Hydrogen-Oxygen Single Cylinder 11.0 kPa Schlieren

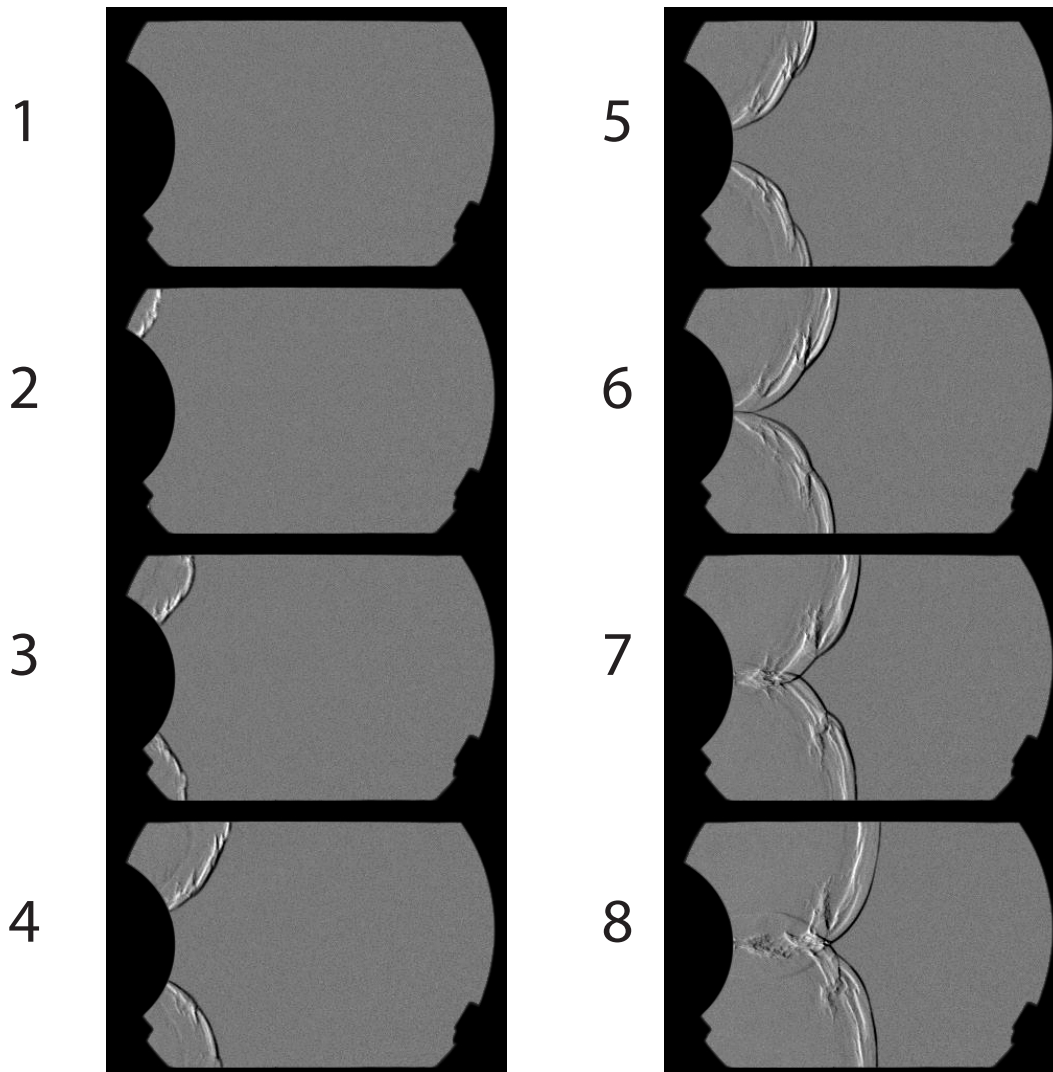


Figure E.8: Schlieren record of hydrogen-oxygen detonation failure around the single cylinder and reactive reflection at $p_0 = 12.4$ kPa. Recorded at $11.62 \mu s$ interframe time, $0.91 \mu s$ exposure, 86058.5 fps.

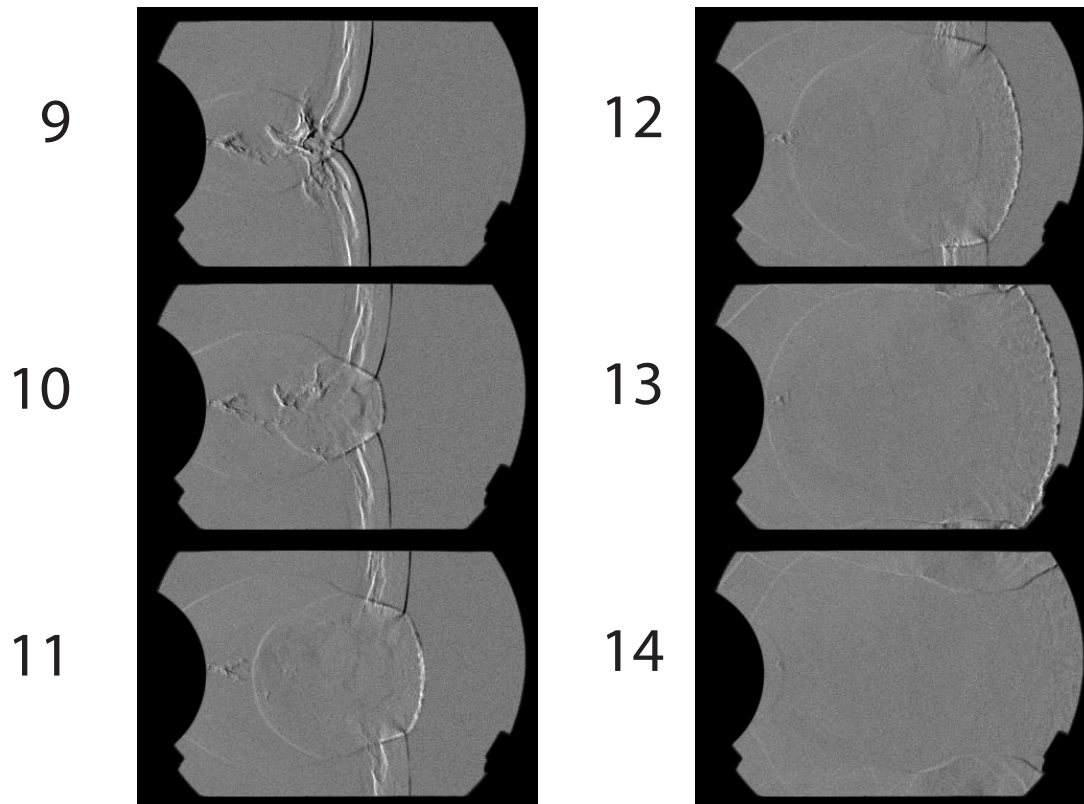


Figure E.9: Schlieren record of hydrogen-oxygen detonation failure around the single cylinder and reactive reflection at $p_0 = 12.4$ kPa. Recorded at $11.62 \mu s$ interframe time, $0.91 \mu s$ exposure, 86058.5 fps.

Hydrogen-Oxygen Single Cylinder 11.0 kPa Schlieren

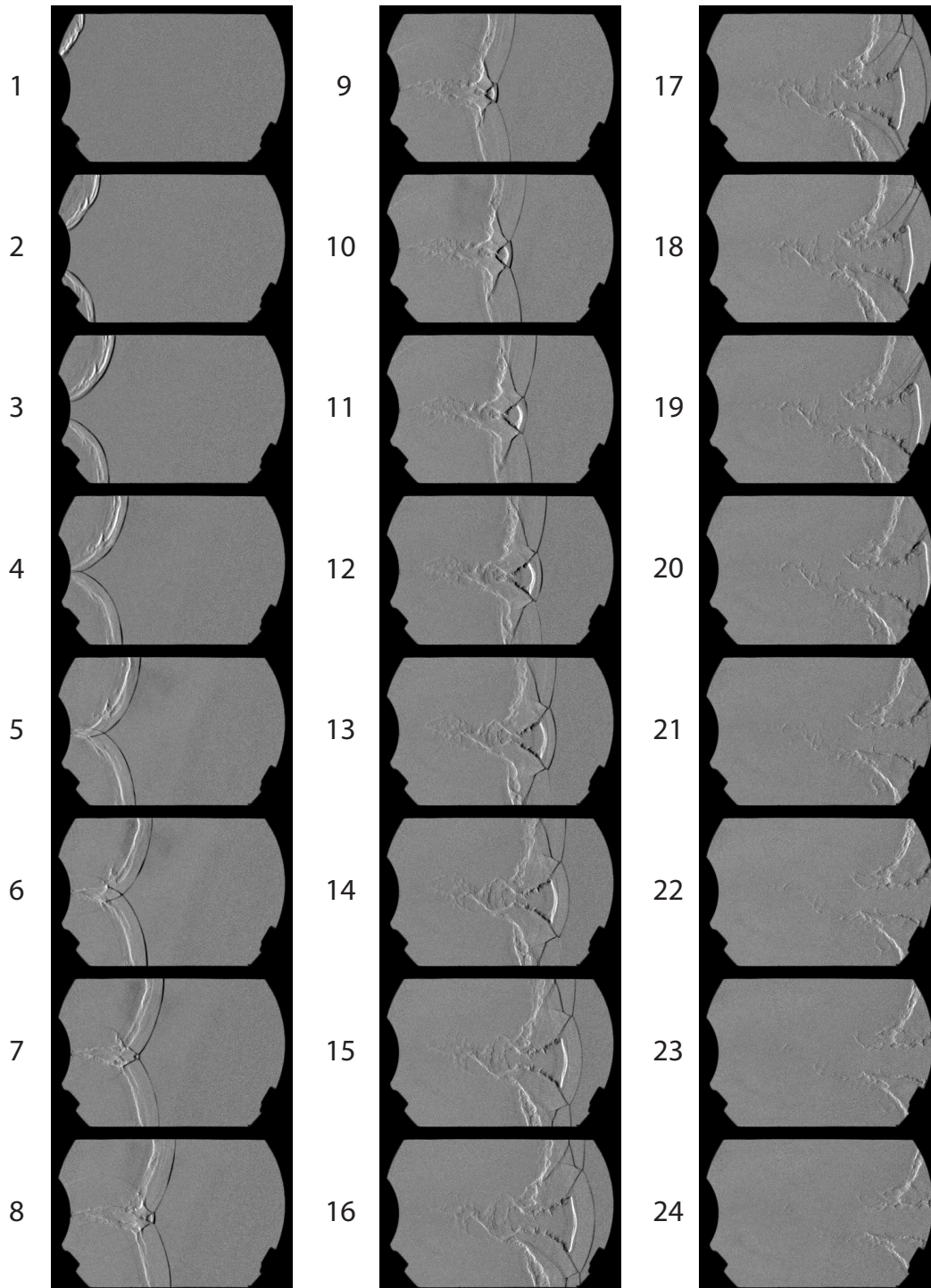


Figure E.10: Shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder and subsequent wave decay at $p_0 = 11.0$ kPa. Recorded at $11.62 \mu s$ interframe time, $0.91 \mu s$ exposure, 86058.5 fps

Hydrogen-Oxygen Single Cylinder 10.3 kPa Schlieren

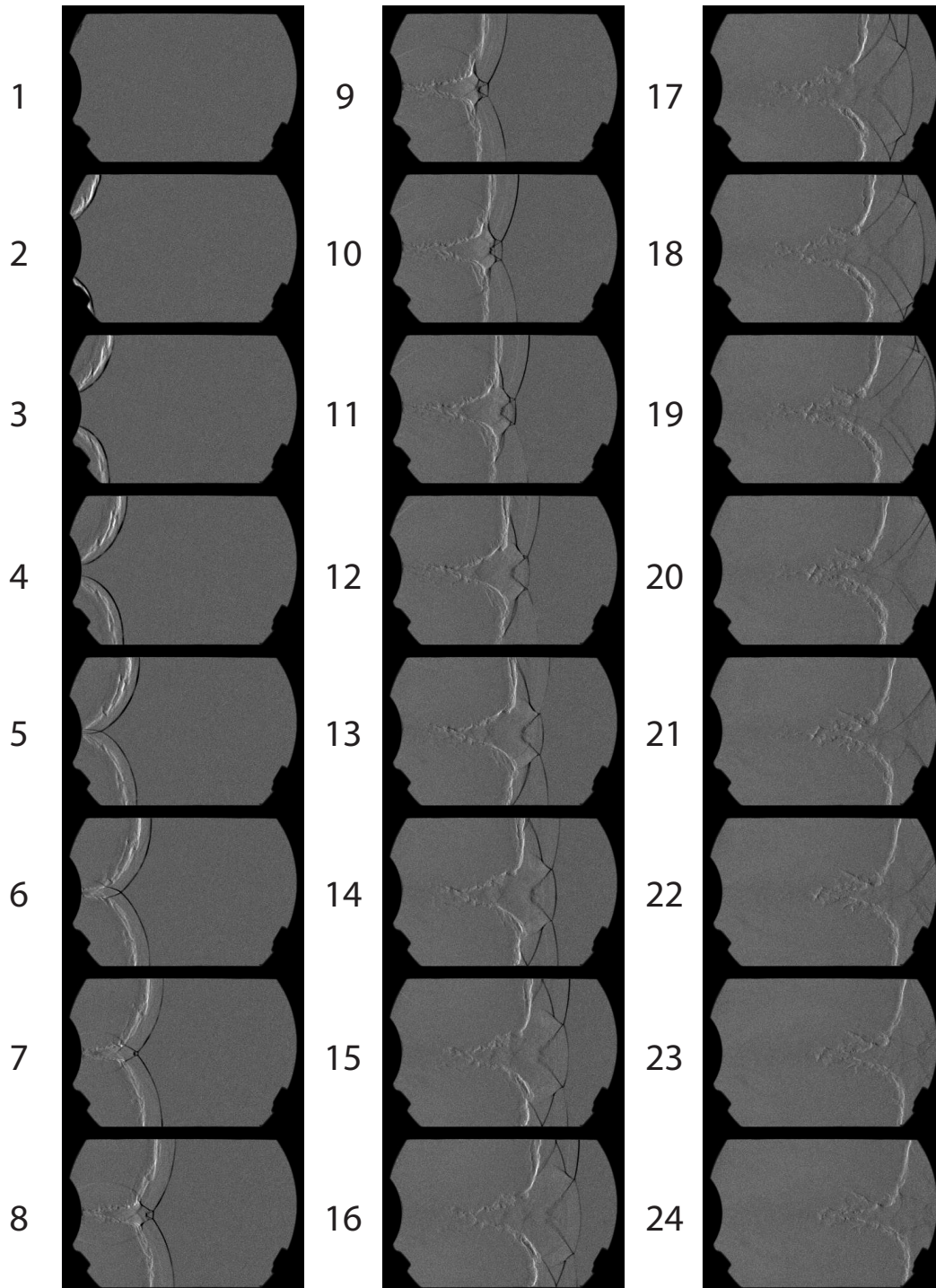


Figure E.11: Complete shadowgraph record of hydrogen-oxygen detonation failure around the single cylinder and un-reactive reflection at $p_0 = 10.3$ kPa. Recorded at $11.62 \mu s$ interframe time, $0.91 \mu s$ exposure, 86058.5 fps.

Appendix F

Methane-Oxygen Experiments

The full experimental records for the experiments discusses above.

F.1 Five Cylinder Experiments

F.1.1 Schlieren Images

Methane-Oxygen Five Cylinder 17.9 kPa Schlieren

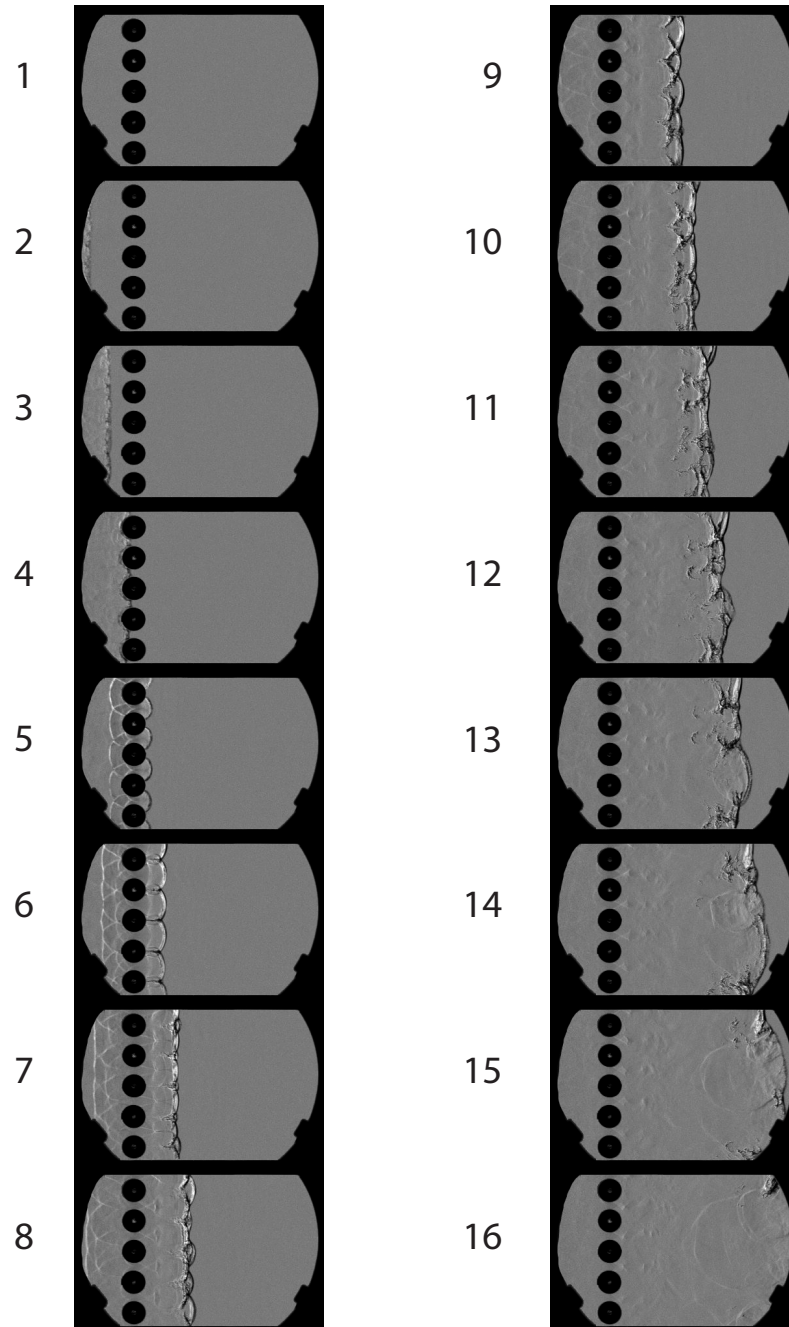


Figure F.1: Full record of Schlieren images illustrating the decay of the fast flame in $\text{CH}_4 + 2\text{O}_2$ $p_0 = 17.9$ kPa. Recorded at $11.62 \mu\text{s}$ interframe time, $0.91 \mu\text{s}$ exposure, 86058.51 fps.

F.1.2 Shadowgraph Images

Methane-Oxygen Five Cylinder 6.89 kPa Shadowgraph

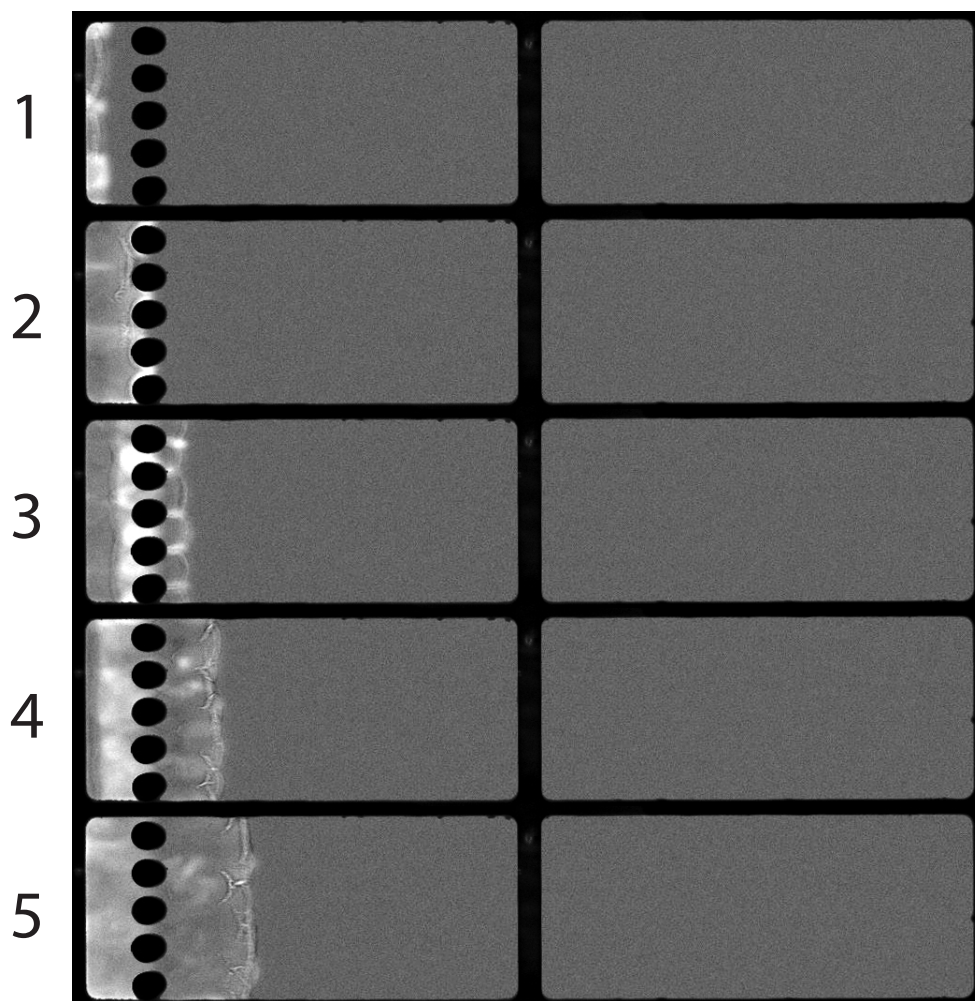


Figure F.2: Part A of Full record of Shadowgraph image illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 6.9$ kPa, 25.63 microseconds, Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps

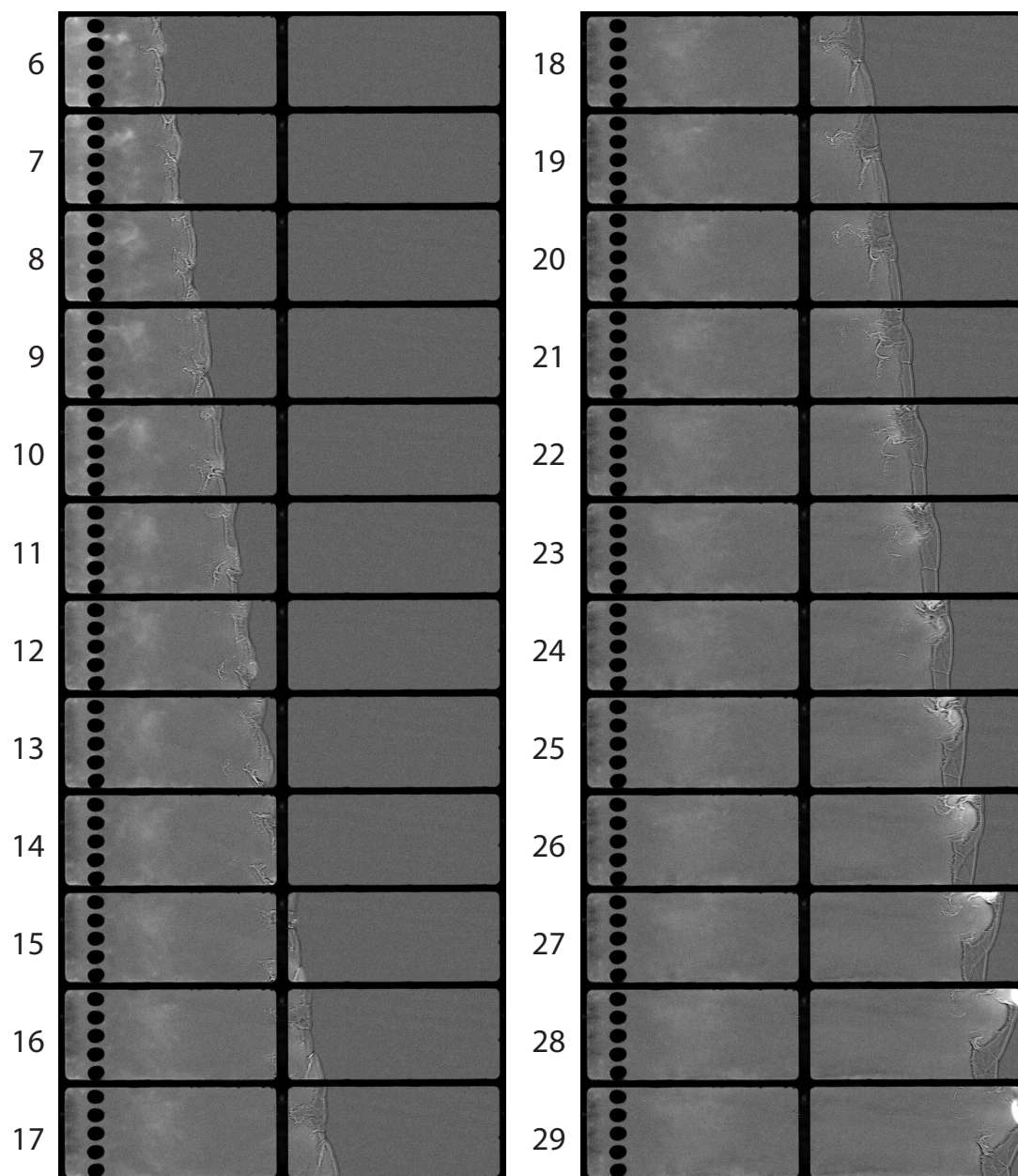


Figure F.3: Part B of Full record of Shadowgraph image illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 6.9$ kPa, 25.63 microseconds, Recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps

Methane-Oxygen Five Cylinder 7.6 kPa Shadowgraph

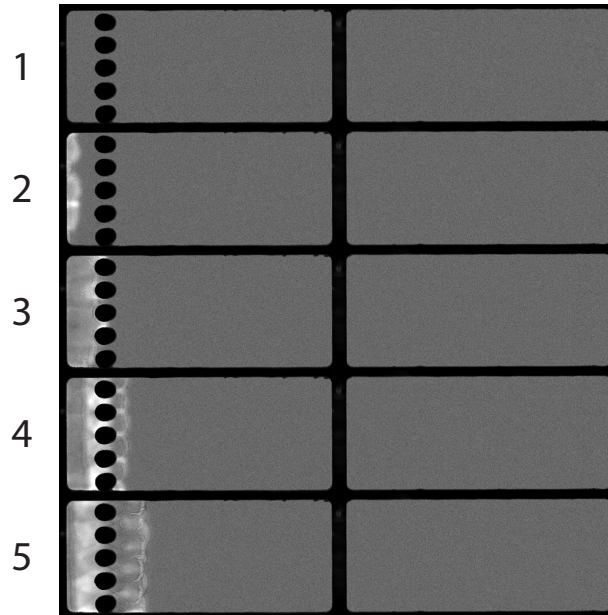


Figure F.4: Frames of the shadowgraph image illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa, 25.63 microseconds, 4.84 microsecond exposure, 39016.7 fps

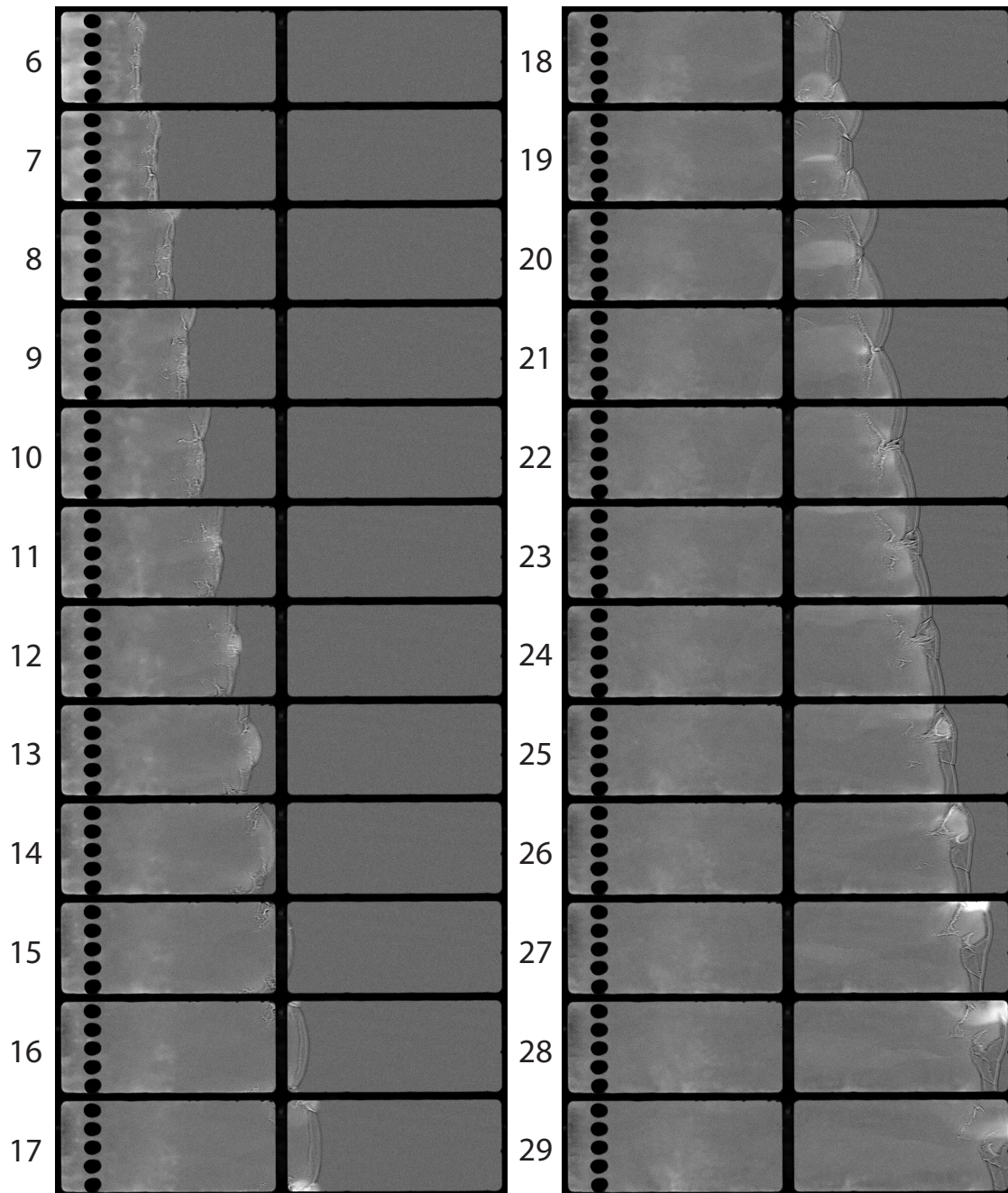


Figure F.5: Frames of the shadowgraph image illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 7.6$ kPa, 25.63 microseconds, 4.84 microsecond exposure, 39016.7 fps

Methane-Oxygen Five Cylinder 8.3 kPa Shadowgraph

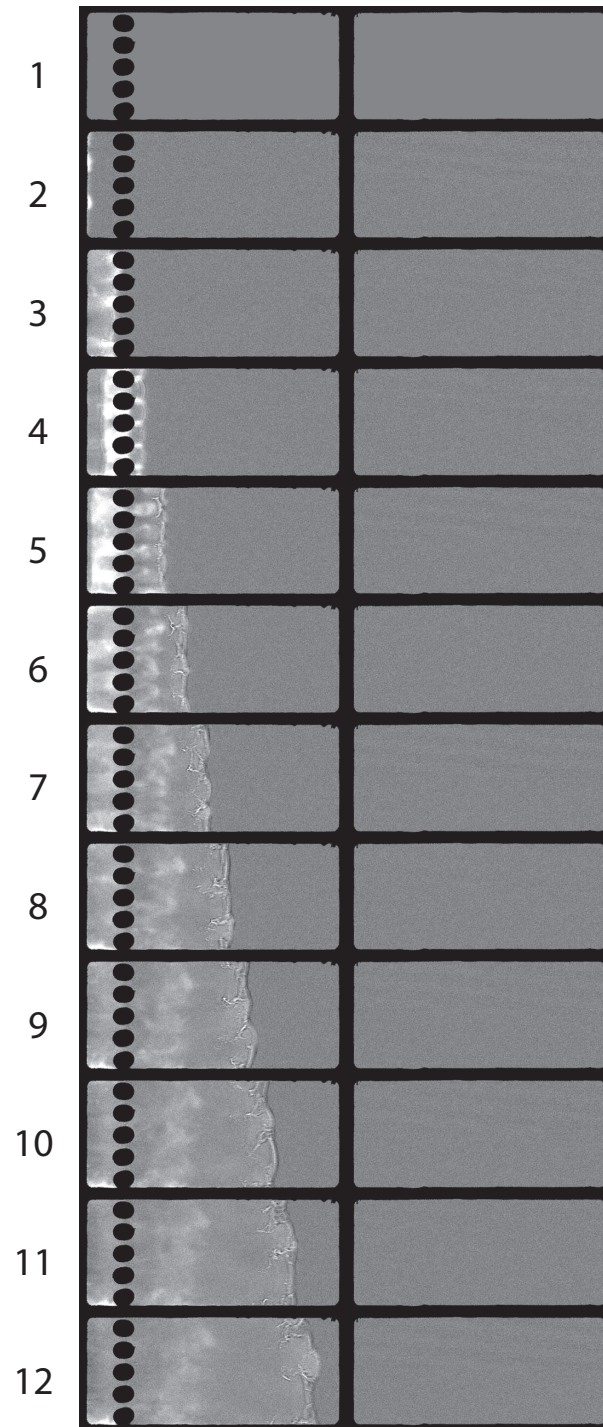


Figure F.6: Full record of Shadowgraph images illustrating the fast flame in $\text{CH}_4\text{-O}_2$, $p_0 = 8.3$ kPa. Recorded at $25.63 \mu\text{s}$, $4.84 \mu\text{s}$ exposure, 39016.7 fps.

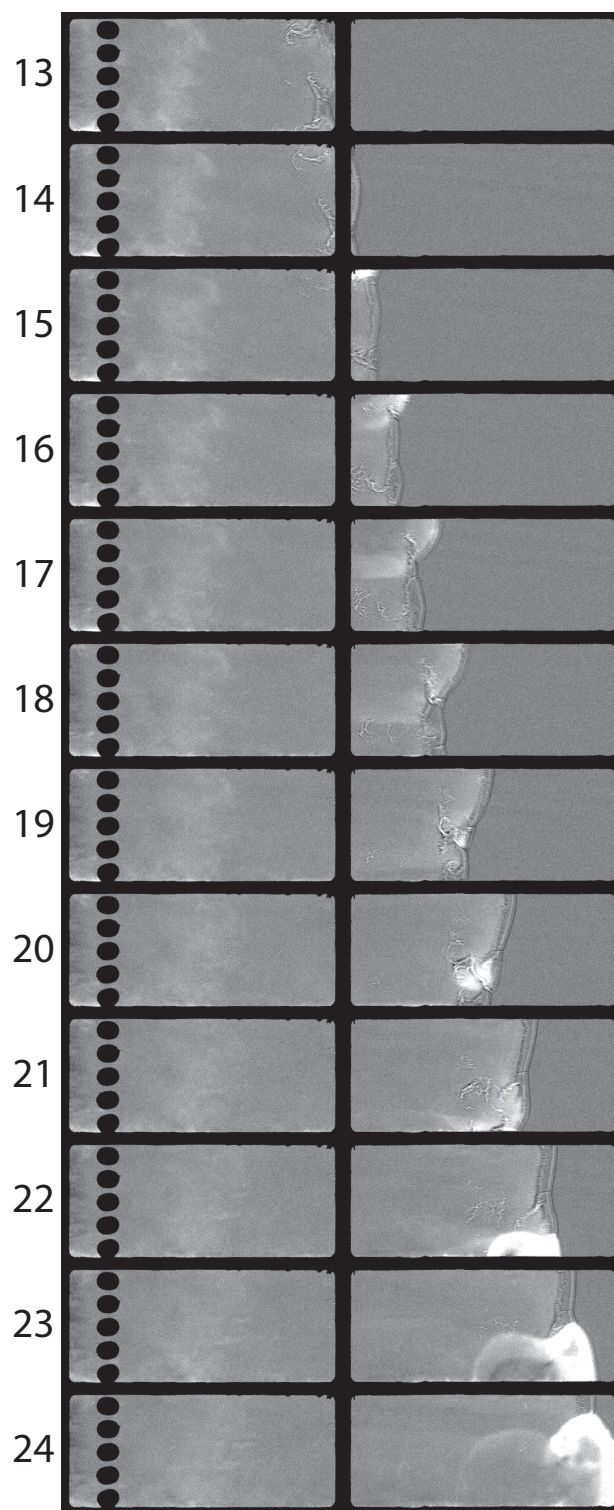


Figure F.7: Full record of Shadowgraph images illustrating the fast flame in CH₄-O₂, $p_0 = 8.3$ kPa. Recorded at $25.63 \mu s$, $4.84 \mu s$ exposure, 39016.7 fps.

Methane-Oxygen Five Cylinder 9.6 kPa Shadowgraph

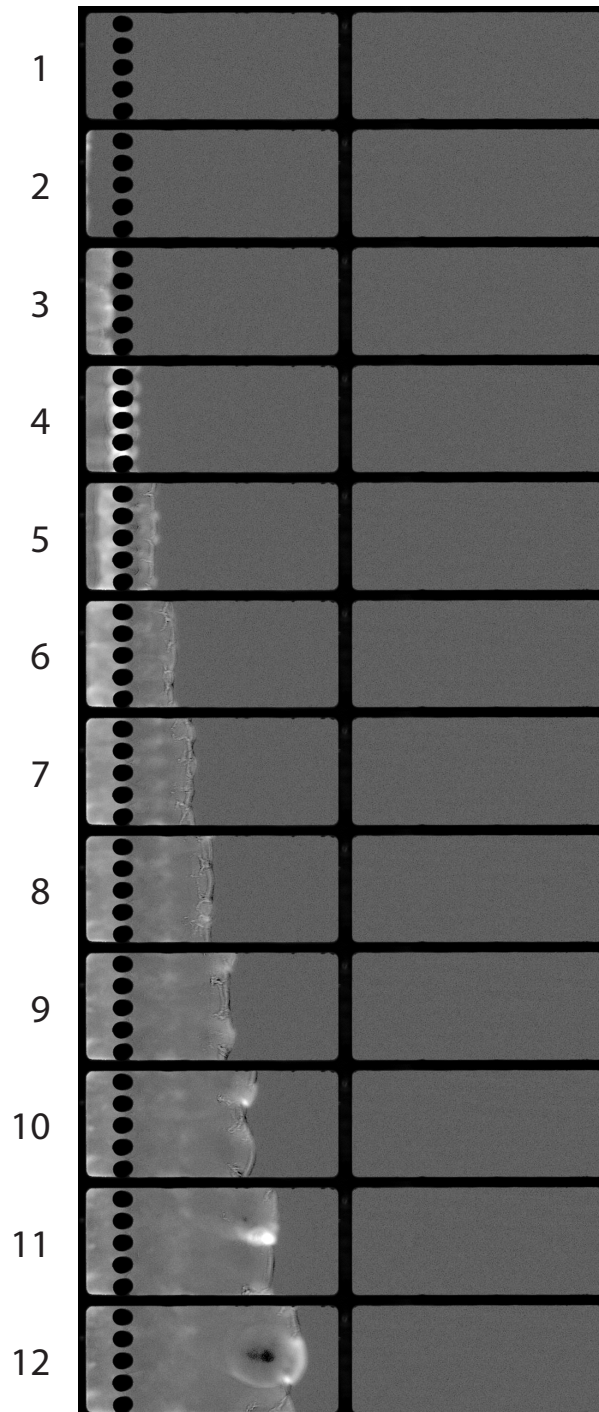


Figure F.8: Full record of shadowgraph images illustrating the fast flame behaviour in $\text{CH}_4\text{-O}_2$, $p_0 = 9.6$ kPa, recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps.

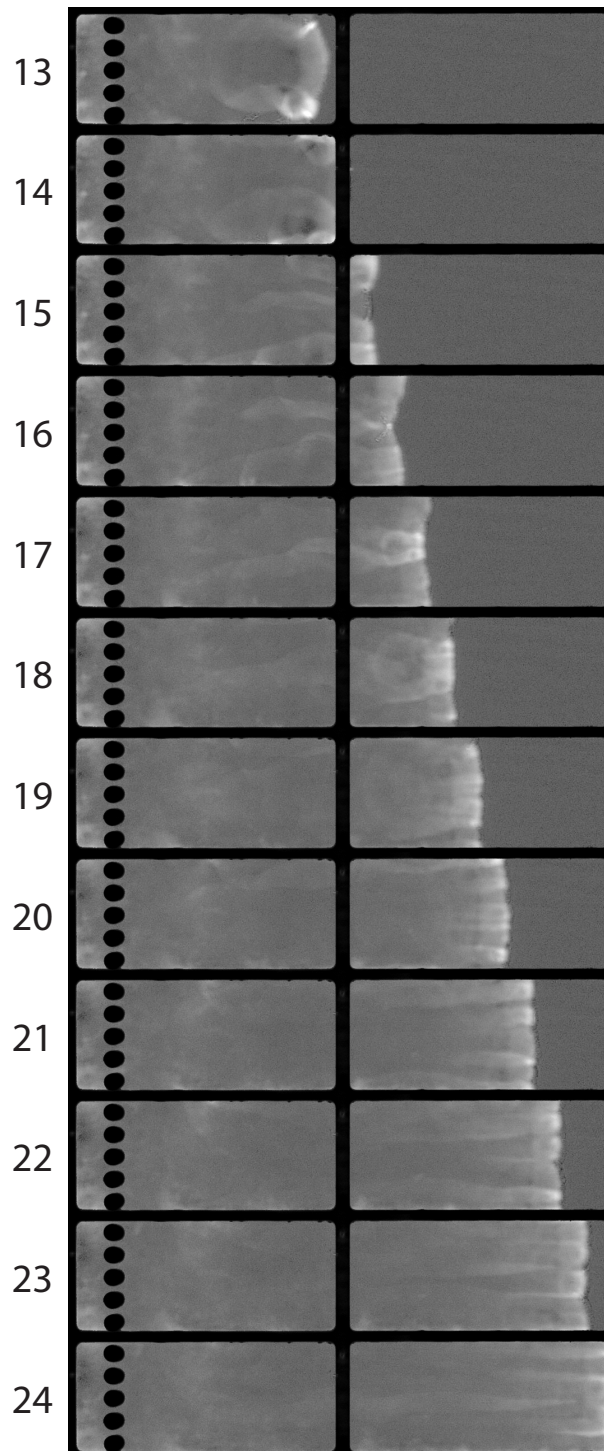


Figure F.9: Full record of shadowgraph images illustrating the fast flame behaviour in $\text{CH}_4\text{-O}_2$, $p_0 = 9.6$ kPa, recorded at $21.72 \mu\text{s}$ interframe time, $4.78 \mu\text{s}$ exposure, 46040.51 fps.

F.2 Single Cylinder Experiments

F.2.1 Schlieren Images

Methane-Oxygen Single Cylinder 8.3 kPa Schlieren

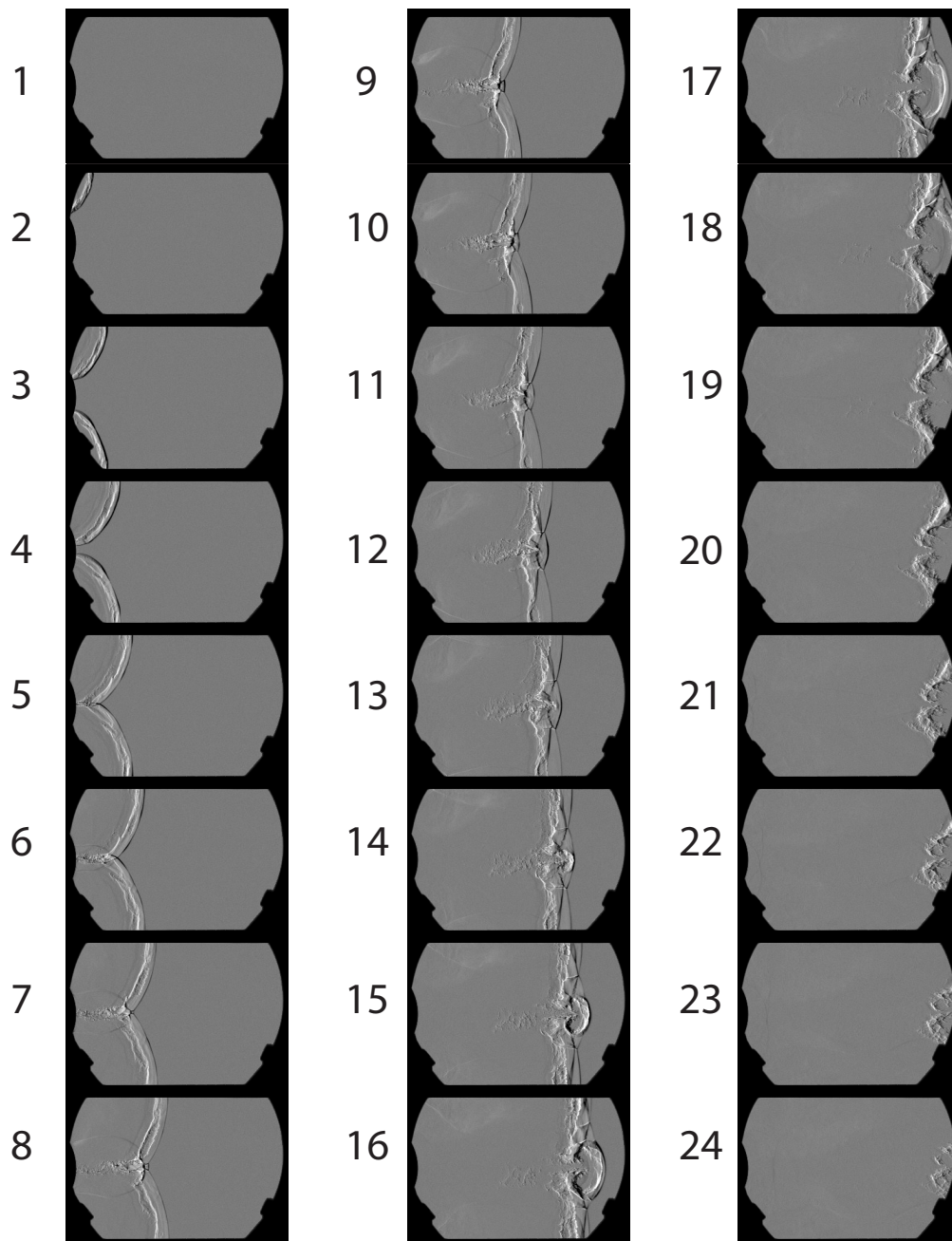


Figure F.10: Full Schlieren record of methane-oxygen forward jet and reaction in jet, $p_0 = 8.3$ kPa. Recorded at $12.91 \mu s$ interframe time, $0.87 \mu s$ exposure, 77459.33 fps.

Methane-Oxygen Single Cylinder 3.5 kPa Shadowgraph

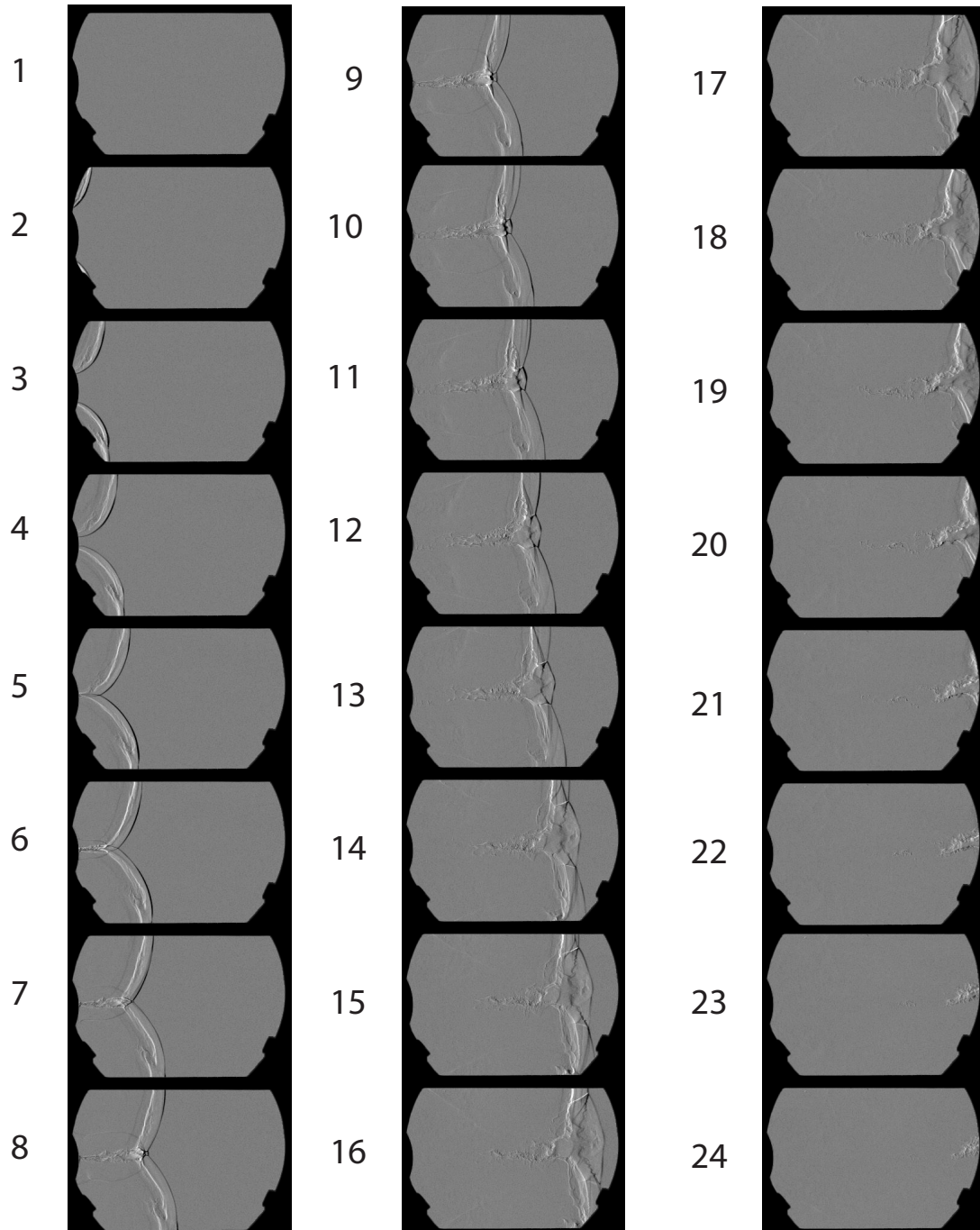


Figure F.11: Schlieren record of methane-oxygen inert shock shock reflection 3.5 kPa

Methane-Oxygen Single Cylinder 8.4 kPa Shadowgraph - 2.5 Channel Heights
Downstream

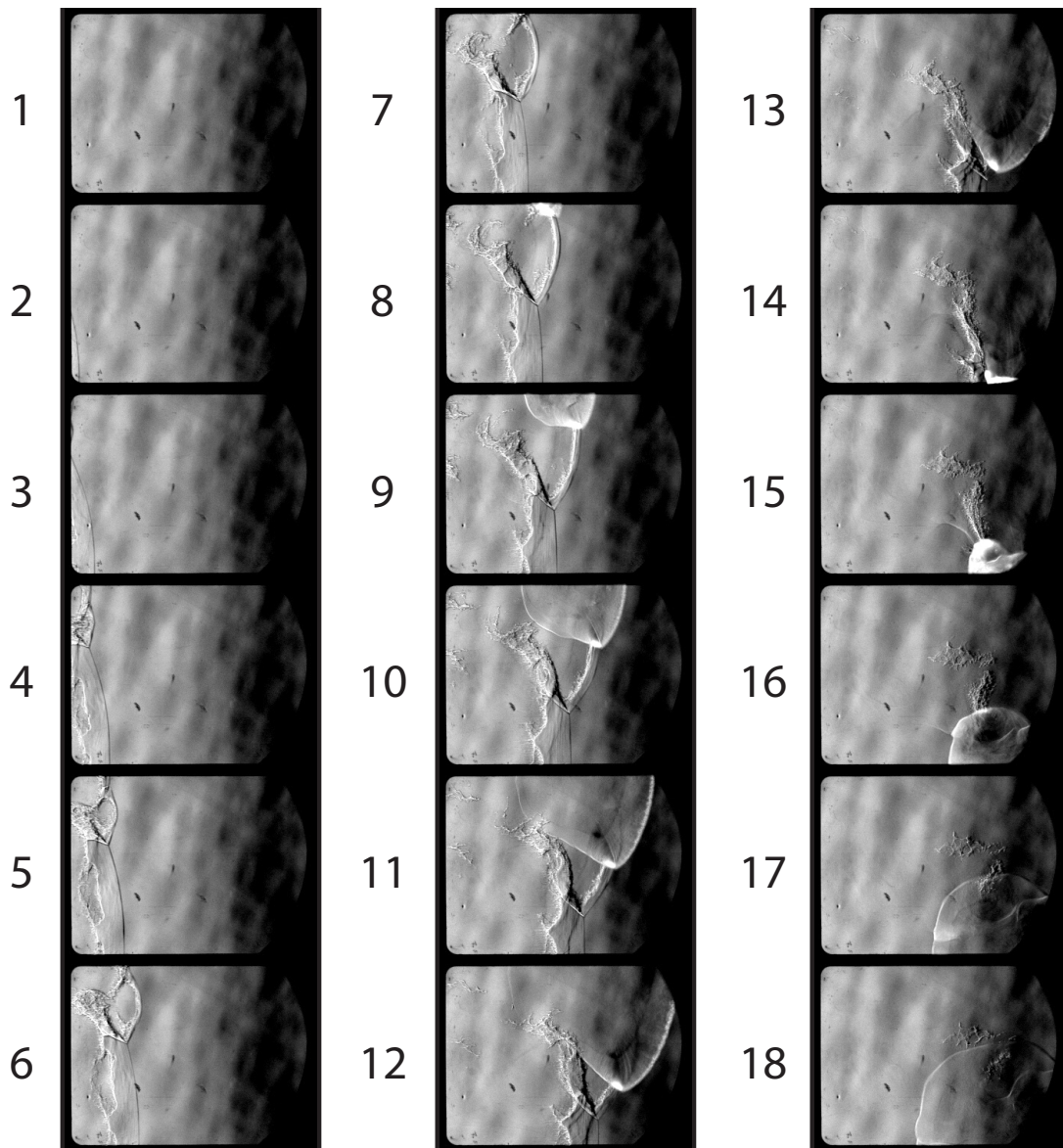


Figure F.12: Full Schlieren record of methane-oxygen forward jet and non-reactive jet, $p_0 = 3.4$ kPa. Recorded at $12.91 \mu s$ interframe time, $0.87 \mu s$ exposure, 77459.33 fps.

F.2.2 Shadowgraph Images

Methane-Oxygen Single Cylinder 13.8 kPa Schlieren

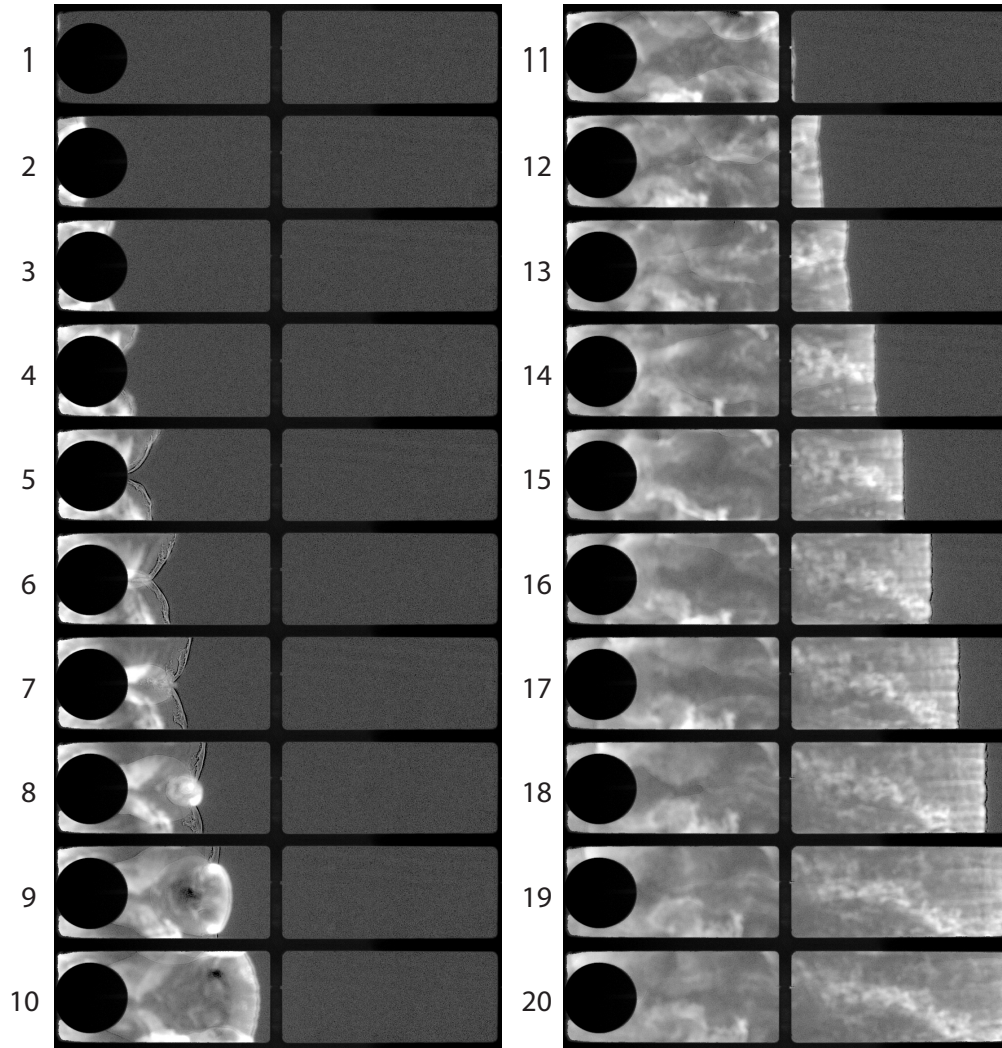


Figure F.13: Full experimental record of shadowgraph record of $\text{CH}_4 + 2\text{O}_2$ re-initiation following interaction with a single cylinder at $p_0 = 13.8$ kPa. Recorded at $25.63 \mu\text{s}$ interframe time, $1 \mu\text{s}$ exposure, 39016.7 fps.

Methane-Oxygen Single Cylinder 11.0 kPa Shadowgraph

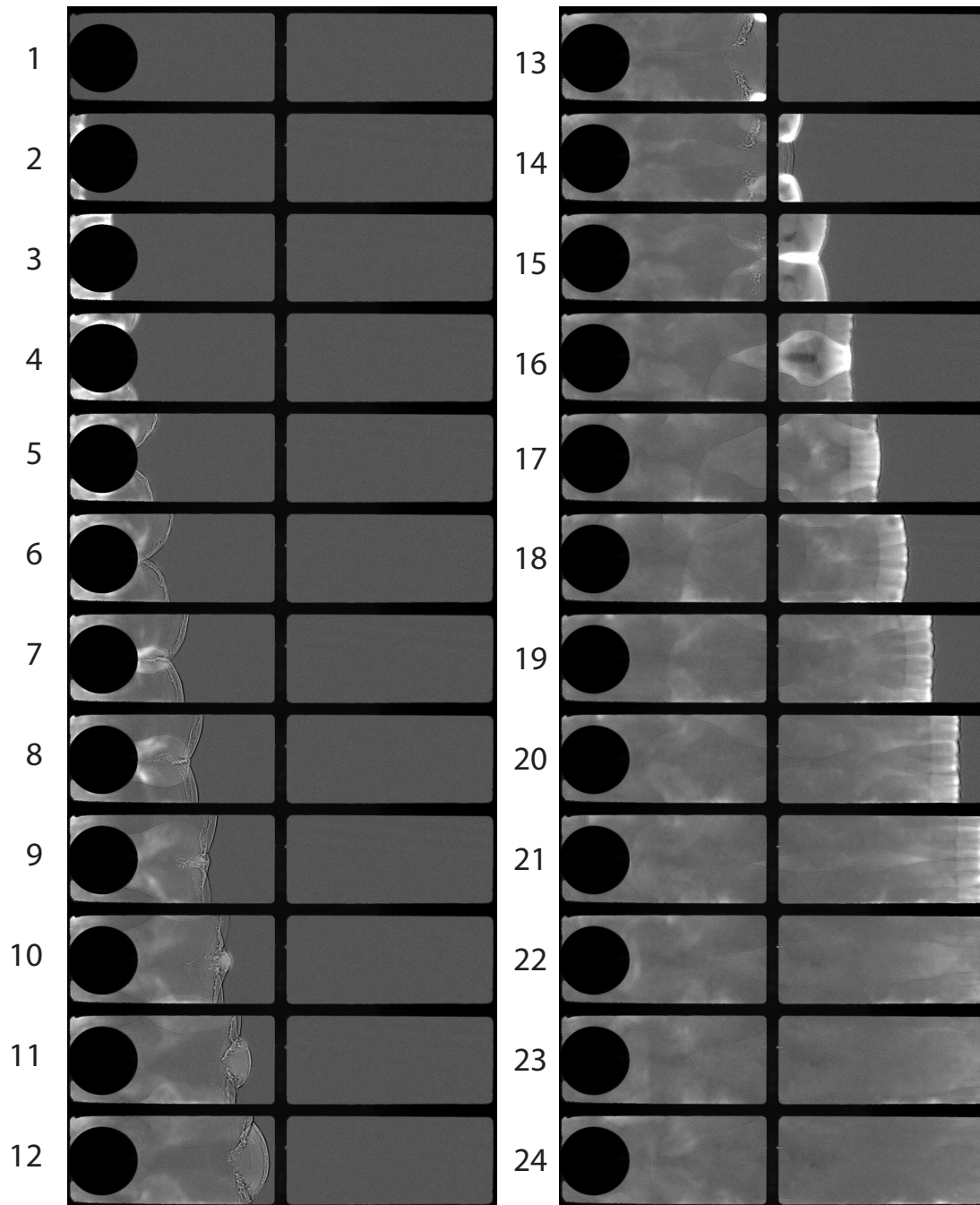


Figure F.14: Shadowgraph record of methane-oxygen detonation initiation upon second reflection, $p_0 = 11.00$ kPa. Recorded at $25.63 \mu s$ interframe time, $1 \mu s$ exposure, 39016.7 fps.

Methane-Oxygen Single Cylinder 9.6 kPa Shadowgraph

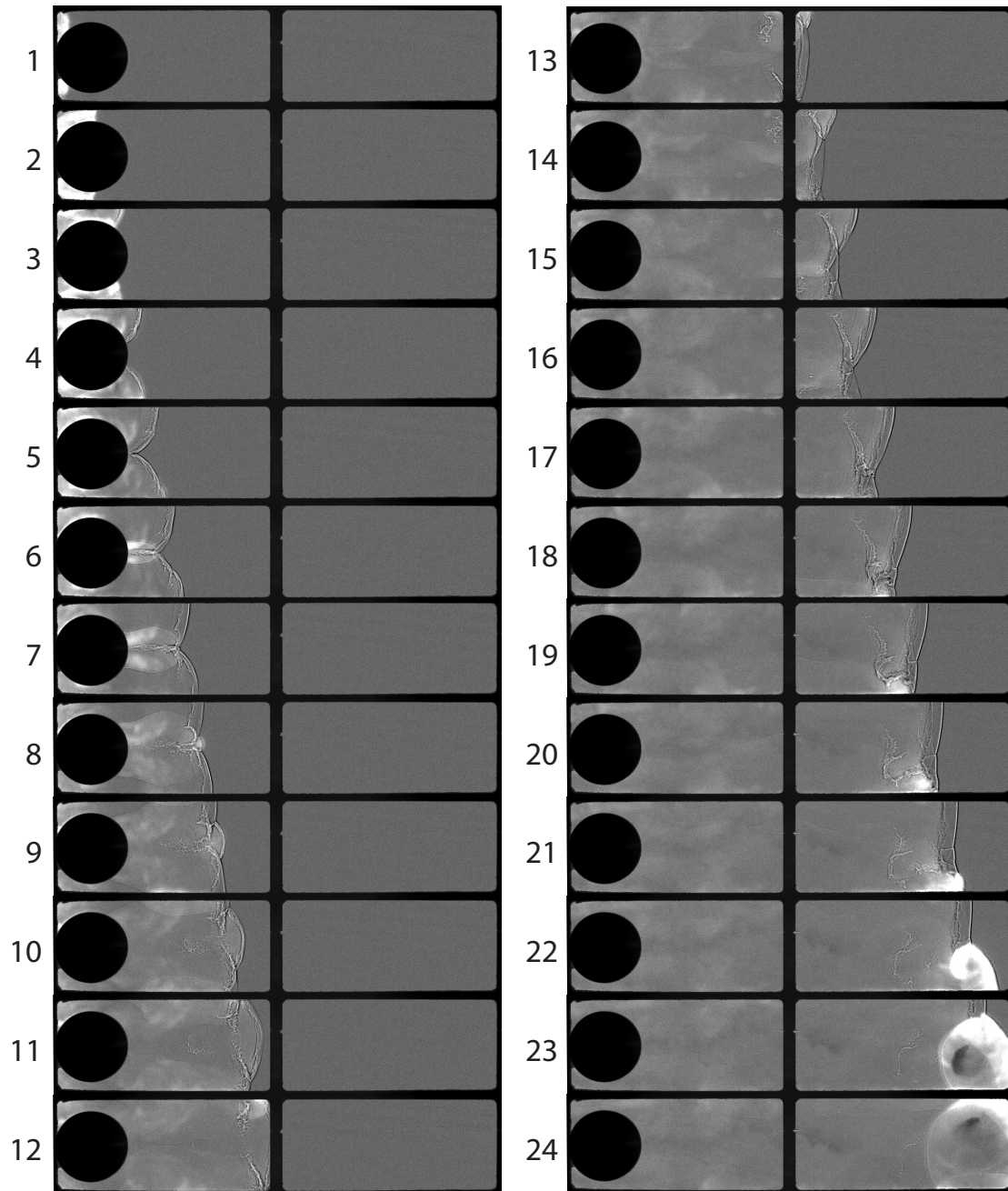


Figure F.15: Full experimental record of shadowgraph record of methane-oxygen detonation initiation upon fourth reflection, $p_0 = 9.6$ kPa. Recorded at $25.62 \mu s$ interframe time, $1 \mu s$ exposure, 39032.0 fps.

Methane-Oxygen Single Cylinder 8.5 kPa Shadowgraph

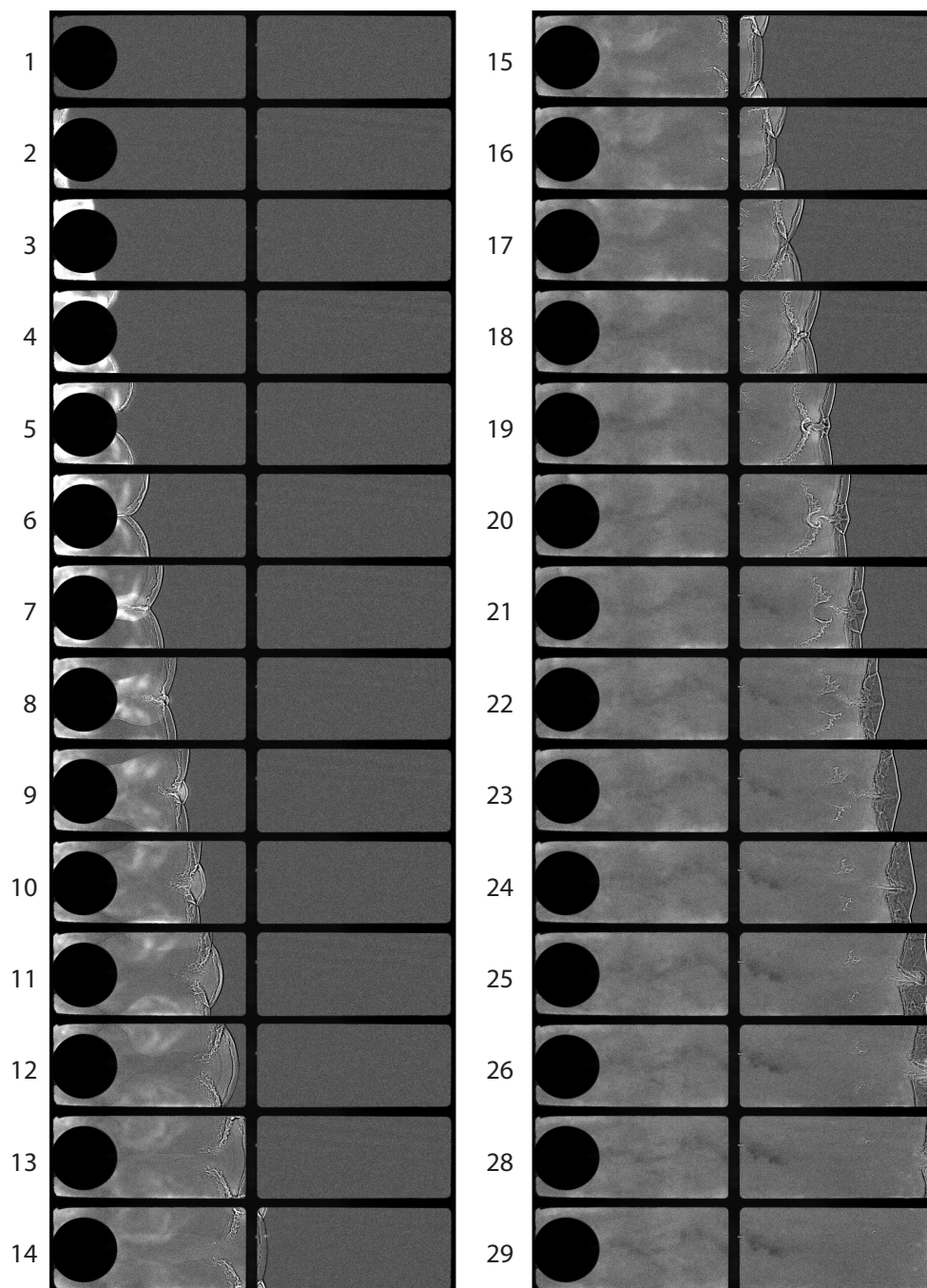


Figure F.16: Full experimental shadowgraph record of methane-oxygen forward jet and delayed reaction in jet, $p_0 = 8.5$ kPa. Recorded at $25.63 \mu s$ interframe time, $1 \mu s$ exposure, 39016.7 fps.

F.2.3 Self-Luminous Experiments

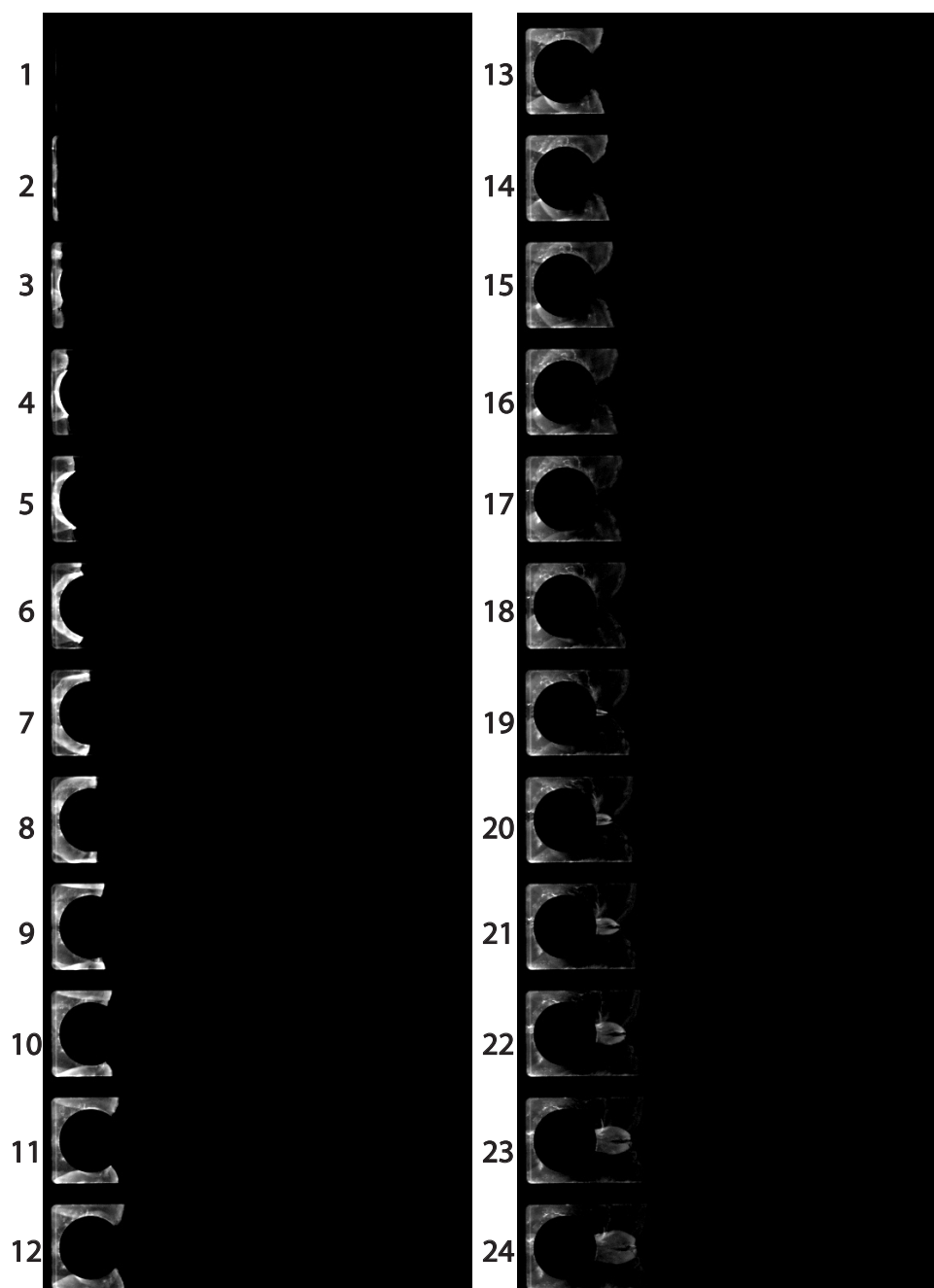
Single Cylinder Self-Luminous $p_0 = 8.5$ kPa

Figure F.17: Part 1 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa

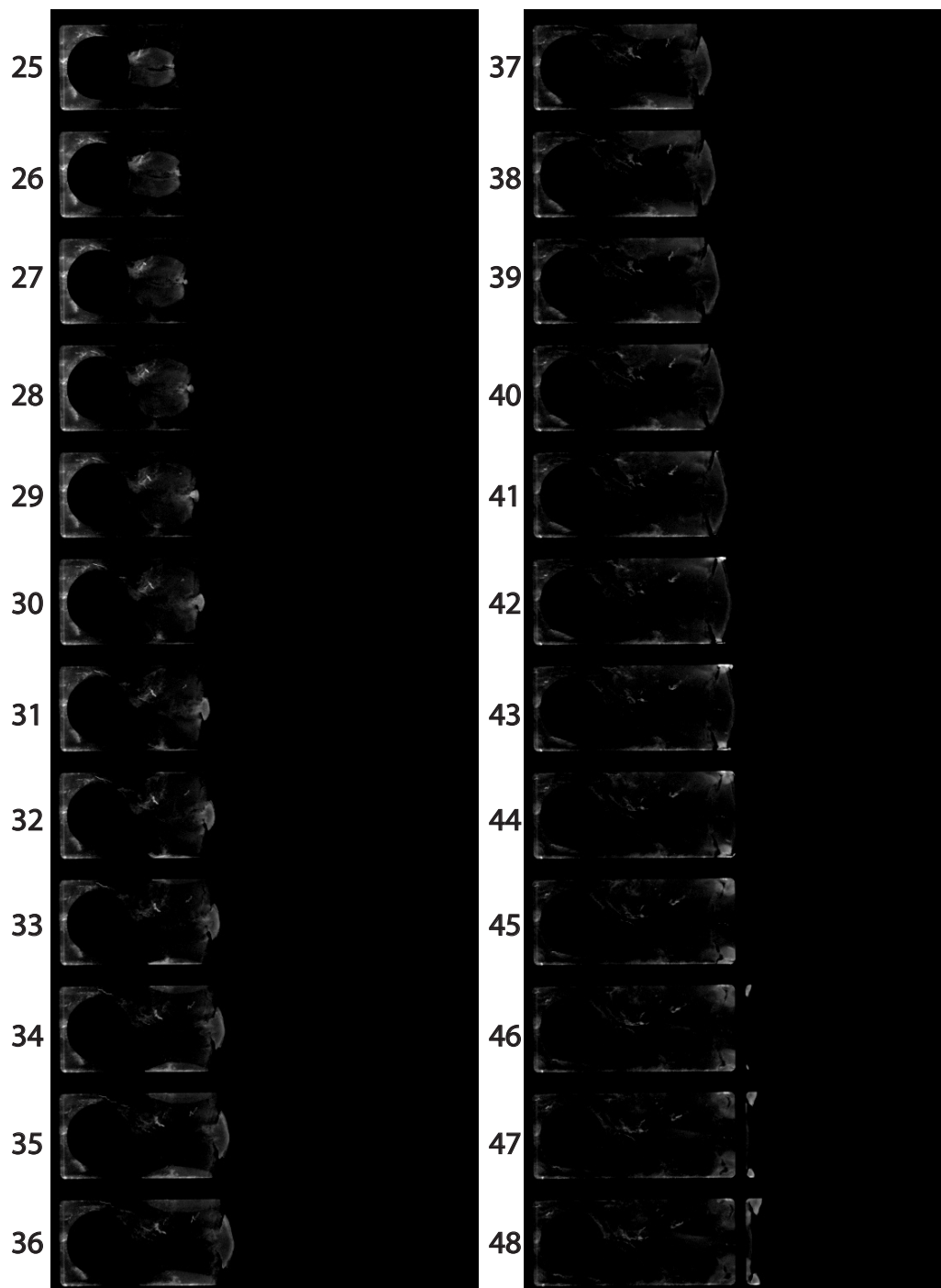


Figure F.18: Part 2 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa

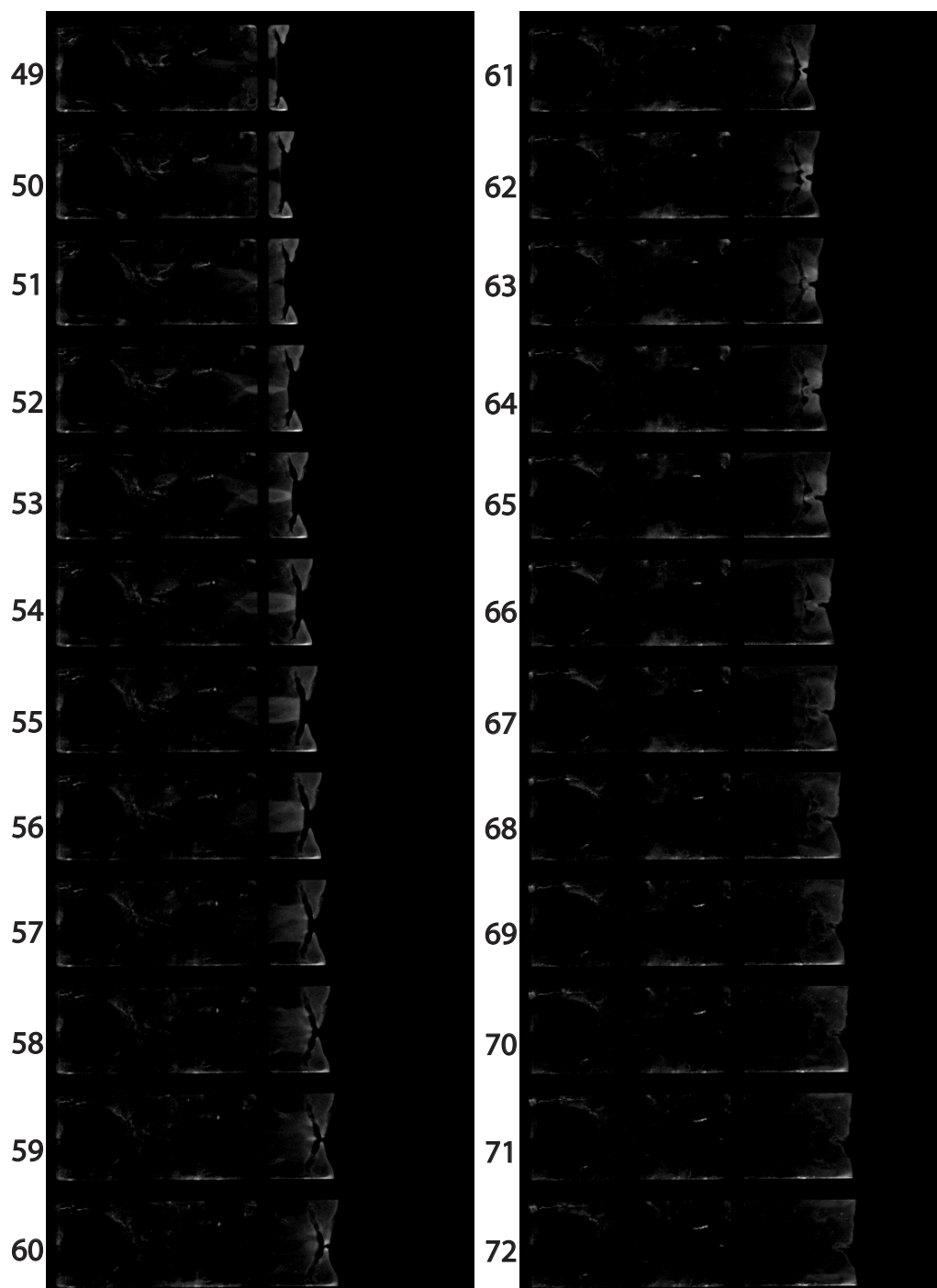


Figure F.19: Part 3 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa

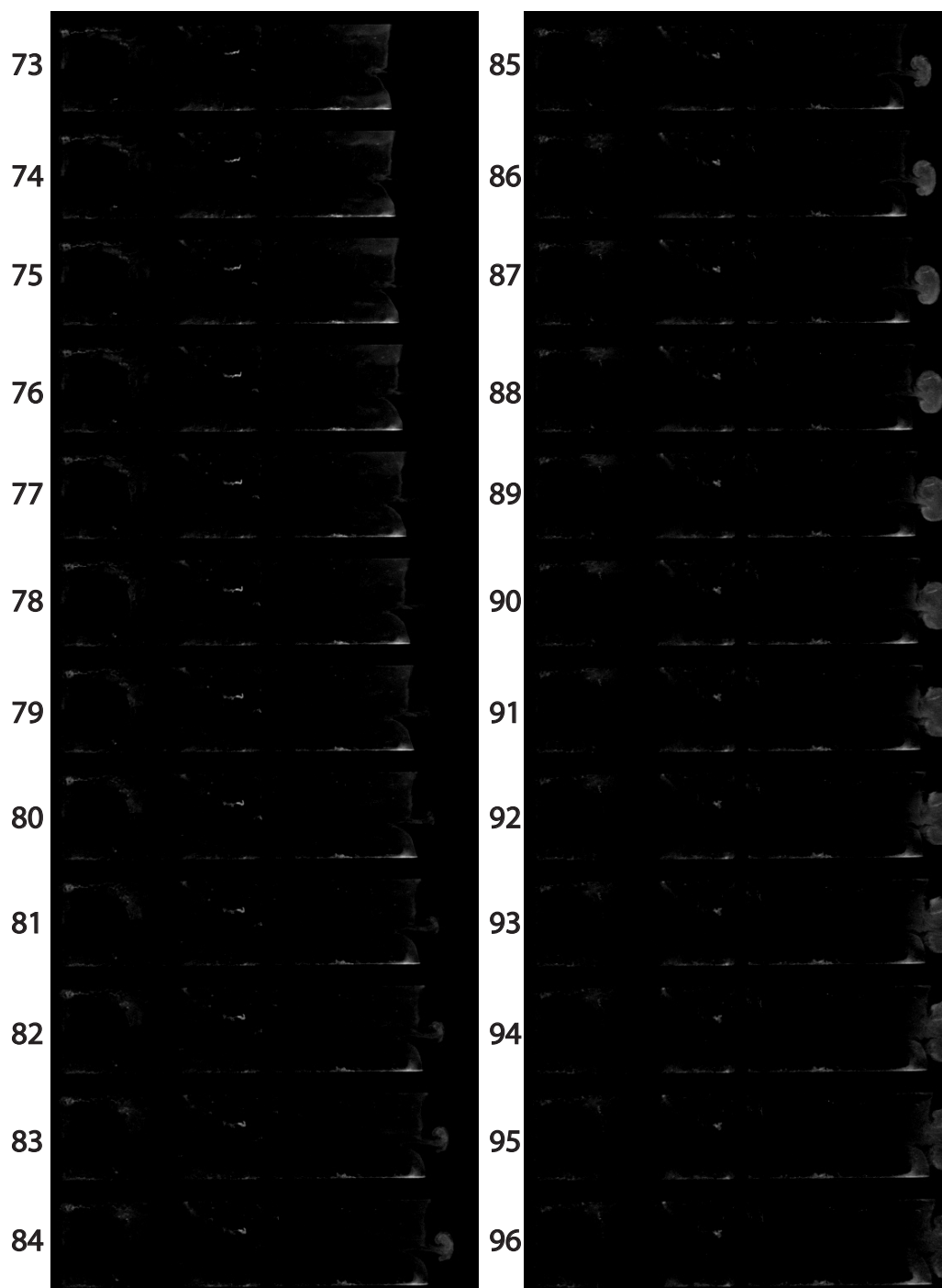


Figure F.20: Part 3 of Full record of direct visualization record of the self luminosity in methane-oxygen at $p_0 = 8.5$ kPa

Single Cylinder Self-Luminous $p_0 = 6.9$ kPa

Figure F.21: Part 1 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa

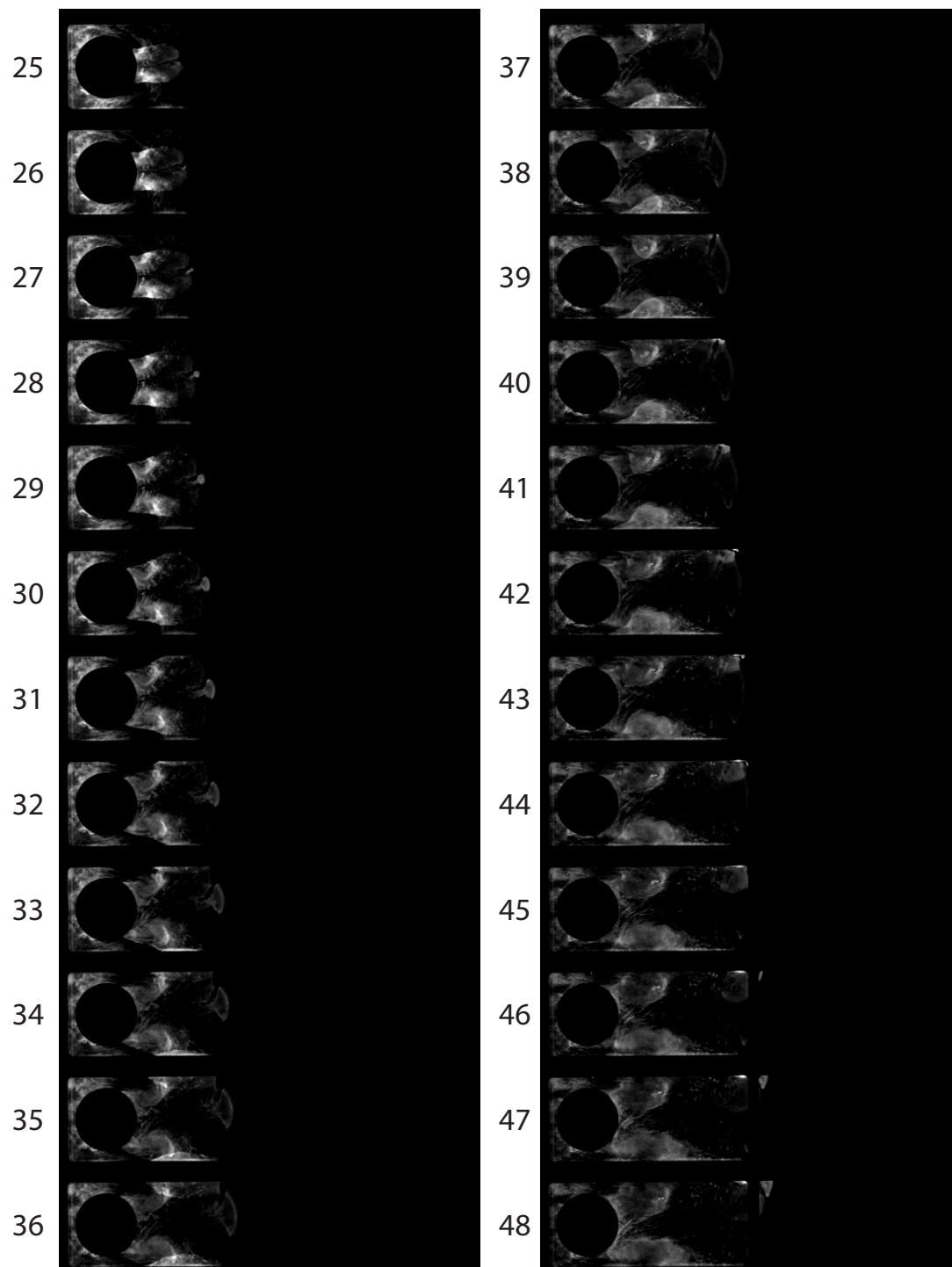


Figure F.22: Part 2 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa

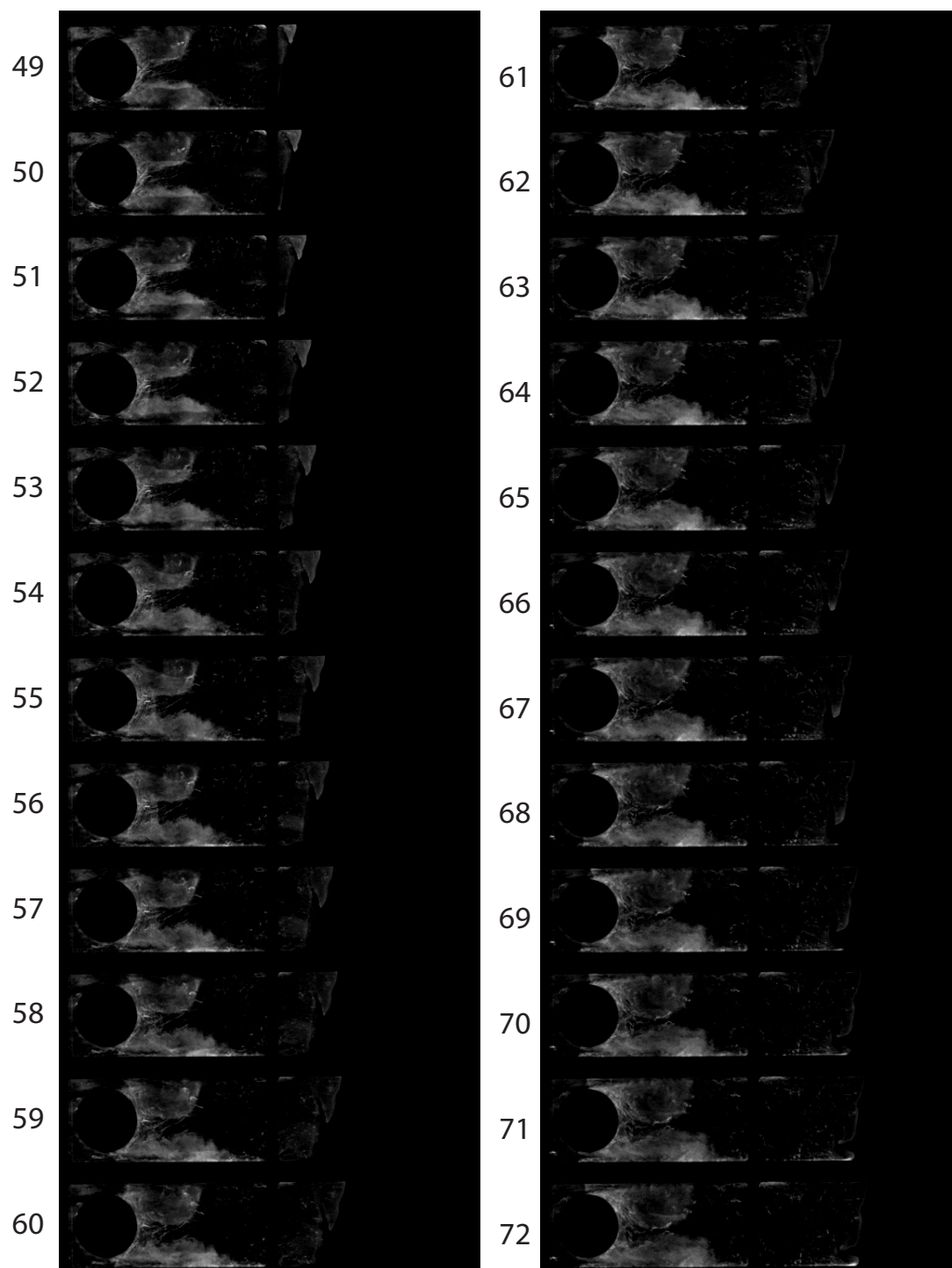


Figure F.23: Part 3 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa

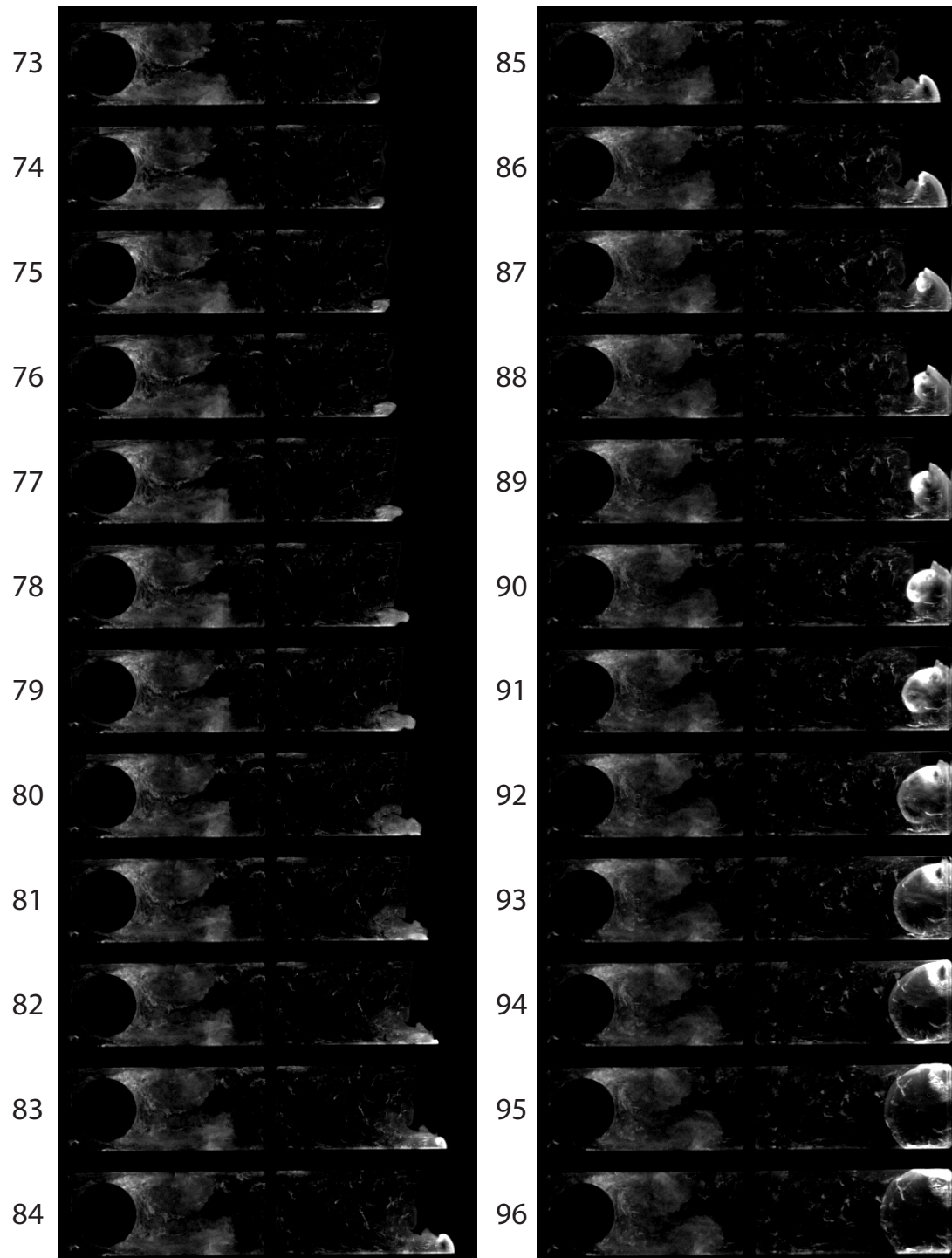


Figure F.24: Part 4 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa

Single Cylinder Self-Luminous $p_0 = 6.9$ kPa

Figure F.25: Part 1 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa

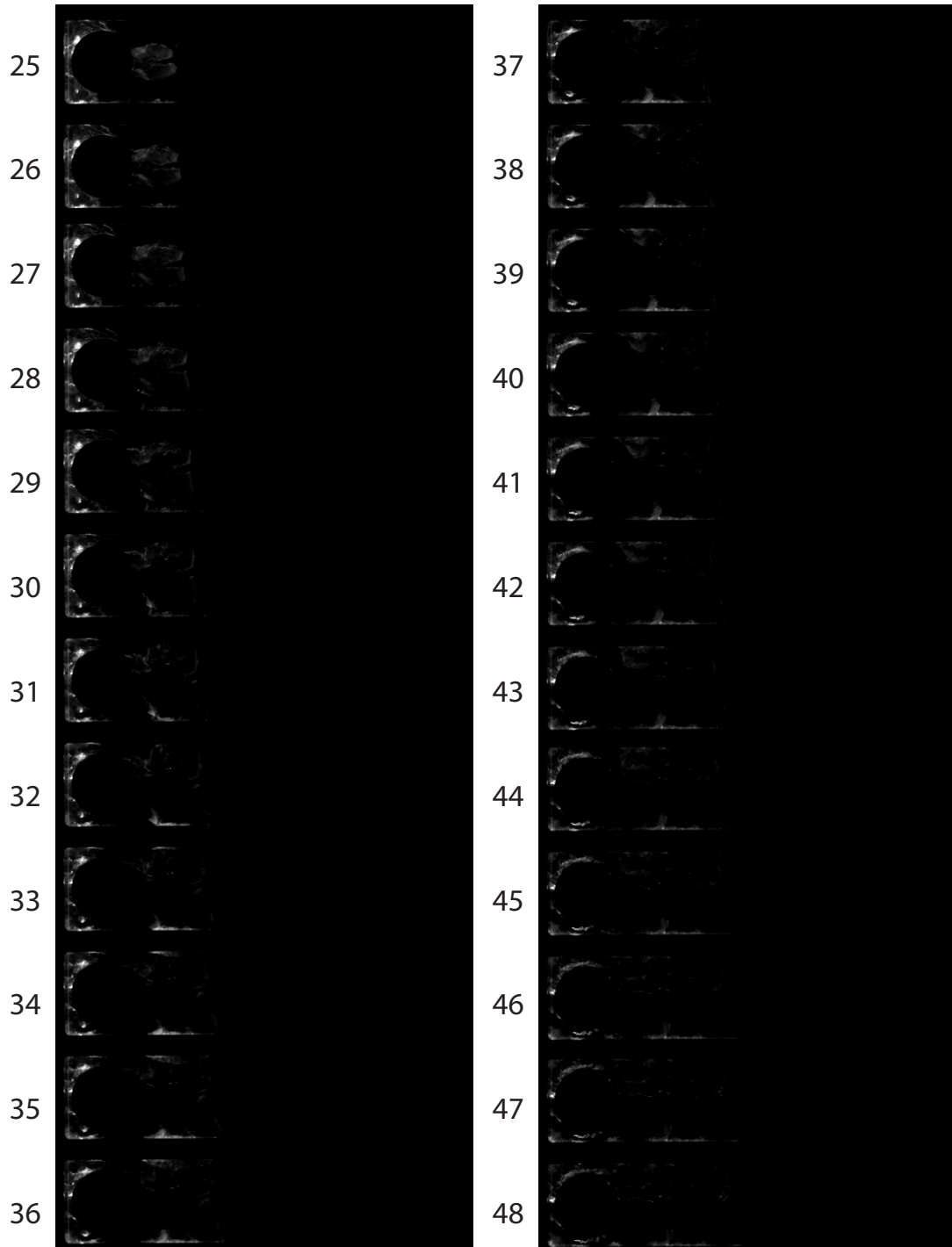


Figure F.26: Part 2 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa

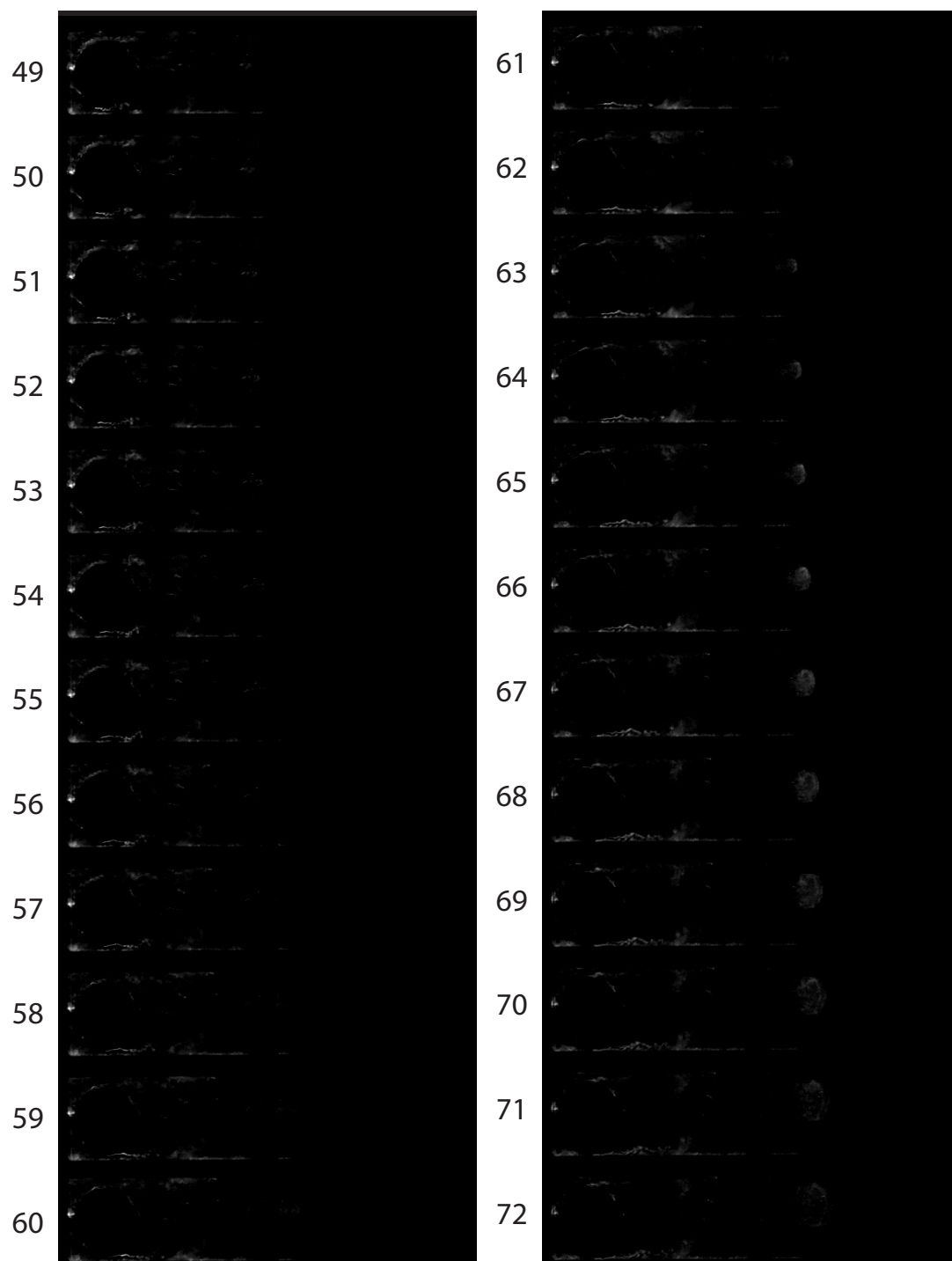


Figure F.27: Part 3 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa

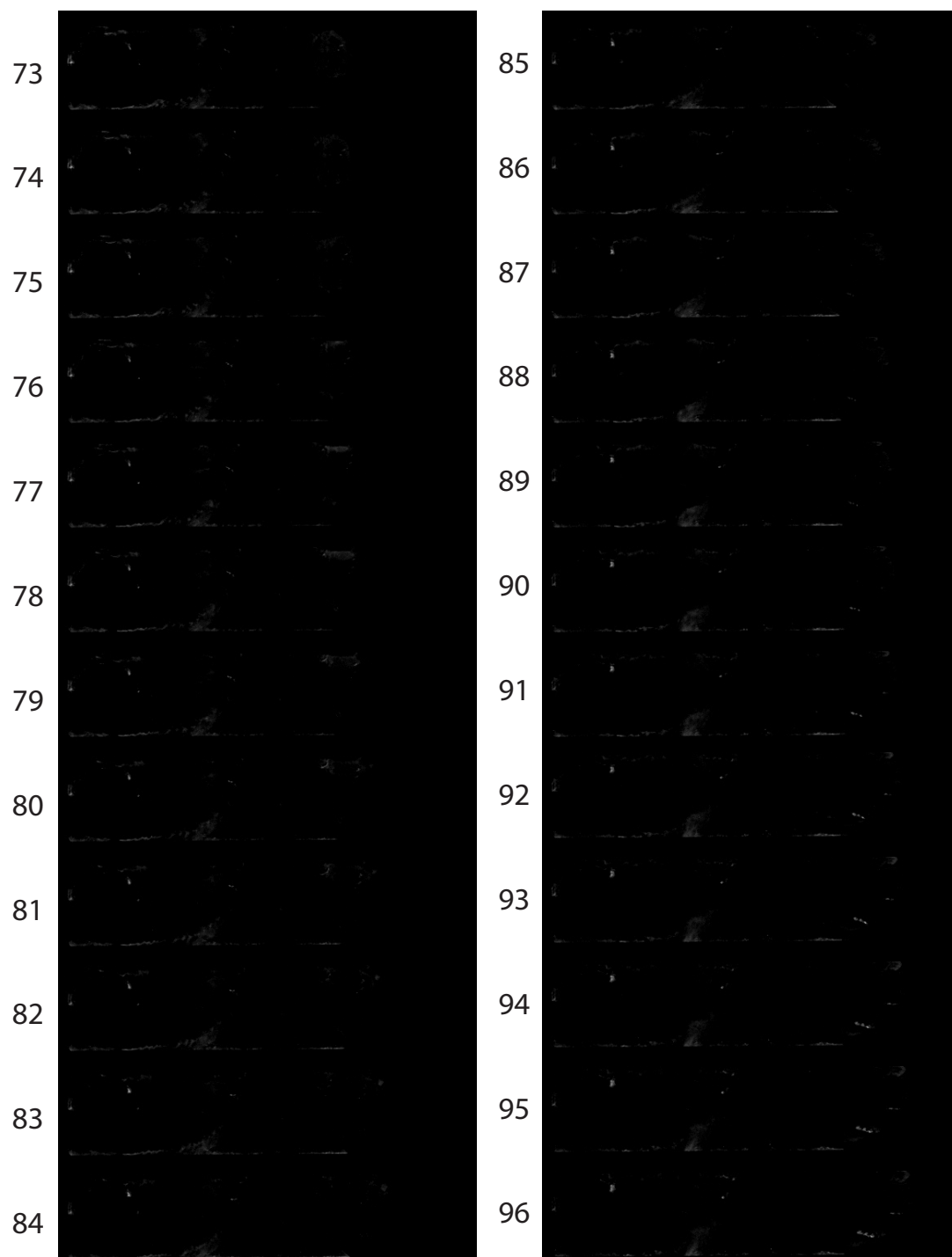
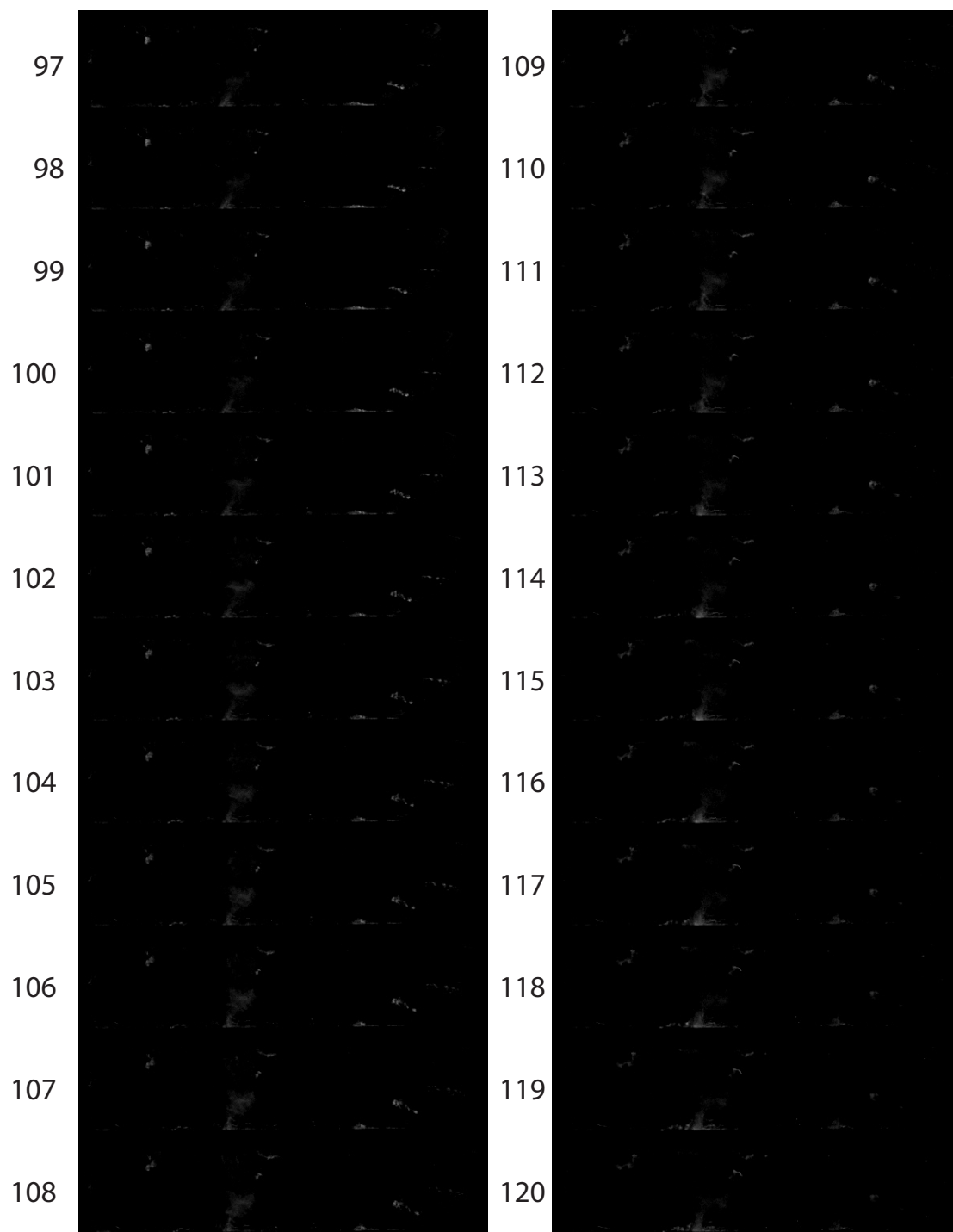


Figure F.28: Part 4 of Direct visualization record of the self luminosity in methane-oxygen at $p_0 = 6.9$ kPa



captionPart 4 of Direct visualization record of the self luminosity in methane-oxygen at
 $p_0 = 6.9$ kPa

Appendix G

Full List of Experiments

Table G.1: A full list of experiments conducted for this study. Results of these experiments have been included as complimentary material.

Optical System	p_0 [kPa]	Test #	Date	Note
Methane-Oxygen				
<i>Single Cylinder</i>				
Shadowgraph	Test 1	9.0	2013-03-20	No-re-initiation
Shadowgraph	Test 2	9.6	2013-03-20	Re-initiation-BottomWall
Shadowgraph	Test 3	9.0	2013-03-20	Re-Initiation-Shock-Shock
Shadowgraph	Test 4	8.5	2013-03-20	Re-initiation-Shock-Shock
Shadowgraph	Test 5	8.5	2013-03-20	No-re-initiation - Jet at the end
Shadowgraph	Test 6	8.3	2013-03-20	No-re-initiation
Shadowgraph	Test 7	8.3	2013-03-20	No-re-initiation
Shadowgraph	Test 8	11.0	2013-03-20	Re-initiation-DoubleWall-Reflection
Shadowgraph	Test 9	11.7	2013-03-20	Re-initiation-Wall-Reflection
Shadowgraph	Test 10	9.3	2013-03-20	Re-initiation-Wall-Reflection
Shadowgraph	Test 1	13.8	2013-03-19	Re-initiation-First-Reflection
Shadowgraph	Test 2	10.3	2013-03-19	Re-initiation-Wall-Reflection
Shadowgraph	Test 3	9.0	2013-03-20	Re-initiation-Last-Reflection
Shadowgraph	Test 4	8.4	2013-03-20	No-re-initiation
Schlieren	Test 8		2013-05-03	Inert Reflection
Schlieren	Test 9	8.6	2013-05-03	Inert Reflection
Schlieren	Test 10	9.6	2013-05-03	Reactive Reflection
Schlieren	Test 11	10.3	2013-05-03	Reactive Reflection
Schlieren	Test 12	11.0	2013-05-03	Reactive Reflection - Clear Jet
Schlieren	Test 13	11.7	2013-05-03	Reactive Reflection - Clear Jet
Schlieren	Test 14	12.4	2013-05-03	Reactive Reflection

Table G.2: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Methane-Oxygen				
<i>Five Cylinder</i>				
Schlieren	Test 1	6.9	2013-08-29	Fast Flame
Schlieren	Test 2	6.9	2013-08-29	Fast Flame
Schlieren	Test 3	10.3	2013-08-29	Fast Flame-Central Symmetric Reflection
Schlieren	Test 4	10.3	2013-08-29	Fast Flame - Asymmetric
Schlieren	Test 5	13.8	2013-08-29	Fast Flame
Schlieren	Test 6	13.8	2013-08-29	Fast Flame - Top wall
Schlieren	Test 7	17.2	2013-08-29	Fast Flame - Central initiation
Schlieren	Test 8	17.2	2013-08-29	Fast Flame - Bottom wall initiation
Schlieren	Test 9	17.2	2013-08-29	Fast Flame - Multi-initiation
Schlieren	Test 10	17.2	2013-08-29	Fast Flame - Symmetric
Schlieren	Test 11	17.9	2013-08-29	Fast Flame - Initiation
Schlieren	Test 12	17.9	2013-08-29	Fast Flame
Schlieren	Test 13	8.3	2013-08-29	Fast Flame
Schlieren	Test 14	8.3	2013-08-29	Fast Flame - Center Jet
Schlieren	Test 15	8.4	2013-08-29	Fast Flame
Schlieren	Test 16	8.4	2013-08-29	Fast Flame
Shadowgraph	Test 1	8.3	2013-08-30	Fast Flame - Top wall initiation
Shadowgraph	Test 2	8.3	2013-08-30	Re-initiation
Shadowgraph	Test 3	8.3	2013-08-30	Fast Flame
Shadowgraph	Test 4	8.4	2013-08-30	Fast Flame - Shock-Shock initiation
Shadowgraph	Test 5	8.4	2013-08-30	Fast Flame - Top/Bottom wall initiation
Shadowgraph	Test 6	8.4	2013-08-30	Fast Flame - Bottom wall initiation
Shadowgraph	Test 7	6.9	2013-08-30	Fast Flame - Top wall initiation
Shadowgraph	Test 8	6.9	2013-08-30	Fast Flame - Top wall initiation
Shadowgraph	Test 9	6.9	2013-08-30	Fast Flame - No initiation
Shadowgraph	Test 10	7.6	2013-08-30	Fast Flame - Symmetric - Clear Jet
Shadowgraph	Test 11	7.6	2013-08-30	Fast Flame - ~Symmetric - Jet
Shadowgraph	Test 12	5.5	2013-08-30	No Initial Detonation
Shadowgraph	Test 13	5.5	2013-08-30	No Initial Detonation
Shadowgraph	Test 14	9.6	2013-08-30	Fast Flame - Shock-Shock Initiation

Table G.3: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Methane-Oxygen				
<i>Single Cylinder</i>	- Center of	Section 2		
Schlieren	Test 1	8.3	2013-01-10	Detonation
Schlieren	Test 2	8.3	2013-01-10	Detonation
Schlieren	Test 3	8.3	2013-01-10	Detonation
Schlieren	Test 4	6.9	2013-01-10	Fast Flame - Reactive Reflection
Schlieren	Test 1	8.4	2013-01-11	Fast Flame - re-initiation
Schlieren	Test 2	8.4	2013-01-11	Fast Flame - Reactive wall reflection
Schlieren	Test 3	8.4	2013-01-11	Unreactive Reflection
Schlieren	Test 4	8.4	2013-01-11	Fast Flame - Reactive Pocket initiates
Schlieren	Test 5	8.4	2013-01-11	Unreactive Reflection
Schlieren	Test 6	8.4	2013-01-11	Fast Flame - asymmetrical reflection
Schlieren	Test 1	6.9	2013-01-14	Unreactive reflection
Schlieren	Test 2	6.9	2013-01-14	Asymmetrical unreactive reflection
Chemi-Luminecent	Test 3	6.9	2013-01-14	Difficult to see
Chemi-Luminecent	Test 4	8.4	2013-01-14	Fast Flame - Initiation
Chemi-Luminecent	Test 1	6.9	2013-01-15	Fast Flame - Initiation at End
Chemi-Luminecent	Test 2	6.9	2013-01-14	Difficult to see

Table G.4: A full list of experiments conducted for this study, continued. Experiments taken with Rohit Bhattacharjee

Optical System	p_0 [kPa]	Test #	Date	Note
Methane-Oxygen				
<i>Single Cylinder</i>				
Schlieren	Test 1	8.3	2012-08-14	Detonation diffraction
Schlieren	Test 3	8.3	2012-08-21	Detonation diffraction
Schlieren	Test 4	3.4	2012-08-14	Inert reflection
Schlieren	Test 5	3.4	2012-08-14	Downstream reflections
Schlieren	Test 6	3.4	2012-08-14	Downstream reflections
Schlieren	Test	8.3		Fast Flame - Clear Jet

Table G.5: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Methane-Oxygen-CO₂				
<i>Single Cylinder</i>				
Schlieren	Test 1	13.8	2013-05-02	Detonation
Schlieren	Test 2	15.2	2013-05-03	Regular shock reflection
Schlieren	Test 3	19.0	2013-05-03	Regular shock reflection
Schlieren	Test 4	17.2	2013-05-03	Regular shock reflection
Schlieren	Test 5	17.2	2013-05-03	Regular shock reflection
Schlieren	Test 6	17.9	2013-05-03	Shock reflection
Schlieren	Test 7	18.9	2013-05-03	Shock reflection
Schlieren	Test 1	13.8	2013-05-07	Failed Experiment
Schlieren	Test 1	17.2	2013-05-08	Shock reflection
Schlieren	Test 2	17.2	2013-05-08	Failed Experiment
Schlieren	Test 1	17.2	2013-05-09	Failed Experiment

Table G.6: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Hydrogen-Oxygen				
<i>Single Cylinder</i>				
Shadowgraph	Test A	10.3	2013-03-01	Reactive reflection
Shadowgraph	Test B	18.9	2013-03-01	Direct detonation transmission
Shadowgraph	Test 1	8.6	2013-03-07	Inert reflection
Shadowgraph	Test 2	12.1	2013-03-07	Reactive reflection
Shadowgraph	Test 3	12.1	2013-03-07	Reactive reflection
Shadowgraph	Test 4	13.8	2013-03-07	Reactive reflection
Shadowgraph	Test 5	15.5	2013-03-07	Direct transmission
Shadowgraph	Test 6	15.2	2013-03-07	Direct transmission
Shadowgraph	Test 7	14.5	2013-03-07	Re-initiation first reflection
Shadowgraph	Test 8	14.1	2013-03-07	Re-initiation first reflection
Shadowgraph	Test 9	13.9	2013-03-07	Direct Transmission
Schlieren	Test 1	12.1	2013-09-05	Fail
Schlieren	Test 2	13.8	2013-09-05	Direct transmission
Schlieren	Test 3	13.4	2013-09-05	First reflection initiation
Schlieren	Test 4	12.4	2013-09-05	First reflection initiation
Schlieren	Test 5	12.1	2013-09-05	Reactive reflection
Schlieren	Test 6	12.1	2013-09-05	Reactive reflection
Schlieren	Test 7	11.0	2013-09-05	Reactive reflection
Schlieren	Test 8	10.3	2013-09-05	Inert reflection
Schlieren	Test 9	10.3	2013-09-05	Inert reflection

Table G.7: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Hydrogen-Oxygen				
<i>Single Cylinder</i>				
Chemi	Test 1	13.8	2013-01-21	First reflection initiation
Chemi	Test 2	13.8	2013-01-21	Not visible
Chemi	Test 3	13.8	2013-01-21	First reflection initiation
Chemi	Test 4	13.8	2013-01-21	First reflection initiation
Chemi	Test 5	15.5	2013-01-21	First reflection initiation
Chemi	Test 2	15.5	2013-01-23	Not visible
Chemi	Test 3	15.5	2013-01-23	First reflection initiation
Schlieren	Test 1	13.8	2014-09-03	First reflection initiation
Schlieren	Test 2	13.8	2014-09-03	First reflection initiation
Schlieren	Test 3	13.1	2014-09-03	First reflection initiation
Schlieren	Test 1	6.9	2014-07-26	Failed Experiment
Schlieren	Test 2	10.3	2014-07-26	Failed Experiment
Schlieren	Test 6	13.8	2014-07-26	Failed Experiment
Schlieren	Test 3	13.8	2014-07-26	Detonation
Schlieren	Test 3	13.8	2014-07-26	Failed Experiment
Schlieren	Test 4	17.2	2014-07-26	Cellular detonation
Schlieren	Test 5	18.6	2014-07-26	Cellular detonation

Table G.8: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Hydrogen-Oxygen				
<i>Five Cylinder</i>				
Chemi	Test 1	13.8	2013-08-21	Detonation initiation
Shadowgraph	Test 1	13.8	2013-08-22	Symmetric reflection
Shadowgraph	Test 2	13.8	2013-08-22	Symmetric reflection
Shadowgraph	Test 3	14.1	2013-08-22	Symmetric reflection
Shadowgraph	Test 4	14.5	2013-08-22	Symmetric reflection
Shadowgraph	Test 5	17.2	2013-08-22	Symmetric reflection
Shadowgraph	Test 6	18.6	2013-08-22	Symmetric reflection

Table G.9: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Propane-Oxygen				
<i>Five Cylinder</i>				
Shadowgraph	Test 1	10.3	2013-08-26	Early initiation
Shadowgraph	Test 2	6.9	2013-08-26	Initiation
Shadowgraph	Test 3	5.1	2013-08-26	Early initiation
Shadowgraph	Test 4	3.5	2013-08-26	Multi local initiation
Shadowgraph	Test 5	2.0	2013-08-26	Forward Jet
Shadowgraph	Test 6	2.0	2013-08-26	Inert reflection
Shadowgraph	Test 7	2.0	2013-08-26	Failed experiment
Shadowgraph	Test 8	2.0	2013-08-26	Forward jet
Shadowgraph	Test 9	2.0	2013-08-26	Failed experiment
Shadowgraph	Test 10	2.8	2013-08-26	Multi local initiation
Schlieren	Test 11	2.8	2013-08-26	Early Structure
Schlieren	Test 1	2.8	2013-08-27	Early Structure
Schlieren	Test 2	2.8	2013-08-27	Early Structure
Schlieren	Test 3	2.0	2013-08-27	Early Structure
Schlieren	Test 4	2.0	2013-08-27	Early Structure
Schlieren	Test 5	3.5	2013-08-27	Initiation at the end
Schlieren	Test 6	3.5	2013-08-27	Early Structure
Schlieren	Test 7	4.1	2013-08-27	Late initiation
Schlieren	Test 8	4.1	2013-08-27	Top wall initiation
Schlieren	Test 9	2.0	2013-08-27	Failed Experiment
Schlieren	Test 10	2.0	2013-08-27	Failed Experiment
Schlieren	Test 11	2.7	2013-08-27	Early Structure
Schlieren	Test 12	2.7	2013-08-27	Early Structure
Schlieren	Test 1	5.1	2013-08-28	Early Structure

Table G.10: A full list of experiments conducted for this study, continued

Optical System	p_0 [kPa]	Test #	Date	Note
Propane-Oxygen				
<i>Five Cylinder</i>				
Shadowgraph	Test 1	6.9	2013-10-03	First reflection initiation
Shadowgraph	Test 2	3.5	2013-10-03	First reflection initiation
Shadowgraph	Test 3	2.8	2013-10-03	First reflection initiation
Shadowgraph	Test 4	2.8	2013-10-03	First reflection initiation
Shadowgraph	Test 2	6.9	2013-10-09	First reflection initiation
Shadowgraph	Test 9	13.8	2013-10-09	Detonation transmission