Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CH4/H2	100/0	1	***1***	1.00	100	-	-	0.145	0.152	230	1 No obstacles in duct. Pure methane starting test mixture. Stoichiometric condition and oxygen met satisfactorily, however flame speeds from IPs not considered reliable. OPs provide flame speeds but latter value appears high. Test 3 will repeat this condition.
CH4/H2	100/0	2	***2***	1.00	100	-	-	0.145	0.152	216	2 No obstacles in duct. Repeat of Test 1 conditions. Stoichiometric condition and oxygen met satisfactorily. Flame speeds and pressures provide satisfactory measurements.
CH4/H2	100/0	3	***1***	1.00	100	-	-	0.145	0.152	232	1a [Repeat of 1] No obstacles in duct. Further repeat of Test 1 conditions. Stoichiometric condition and oxygen met satisfactorily. Data is not considered to be fully satisfactory, e.g. IP flame sensors appear to carry high level of noise. Some OP sensors provide flame speed data. Pressures are consistent with previous test.
CH4/H2	100/0	4	***2***	1.00	100	-	-	0.145	0.152	232	2a [Repeat of 2] No obstacles in duct. Completion of data set for CH4 at equivalence ratio of 1.0. Stoichiometric condition and oxygen met satisfactorily. Data set is satisfactory.
CH4/H2	40/60	5	***6***	0.65	40	60	-	0.145	0.152	168	6a No obstacles in duct. First of series using 40/60 CH4/H2. Stoichiometric condition and oxygen met satisfactorily. Useful data obtained although low equivalence and weak flame results in incomplete record for IPs and OPs. Flame speeds are low as are peak pressures.
CH4/H2		6	***6***		-	-	-		0.152		6abc MkII. Engine failed. Incomplete
CH4/H2	40/60	7	**-**	0.85	40	60	-	0.143	0.153	204	**Test added following engine replacement and to provide further data with 40/60 CH4/H2 mixture** 62 No obstacles in duct. Target equivalence ratio was 0.85. 2nd equivalence ratio for this mixture (40/60 CH4/H2). Stoichiometric condition and oxygen met satisfactorily. Useful data obtained and strong flame provides good flame speeds on both IP and OP sensors.
CH4/H2	40/60	8	**-**	0.86	40	60	-	0.143	0.153	205	**Test added to provide further data with 40/60 CH4/H2 mixture** 62a No obstacles in duct. Target equivalence ratio was 1.0. However, decreasing available pressure in mixed gas reservoir resulted in actual equivalence ratio of 0.86. This is nearly identical to test 7. Oxygen target met satisfactorily. As for test 7, the equivalence ratio for this mixture (60/40 H2/CH4) resulted in a strong flame and provides good flame speeds on both IP and OP sensors
CH4/H2	0/100	9	***4***	0.40	-	100	-	0.143	0.153	73	No obstacles in duct. Target equivalence ratio is 0.4 First of series using 100% H2. Stoichiometric condition and oxygen met satisfactorily. Useful data obtained although low equivalence and weak flame results in an absence of signals for the IPs suggesting flame front doesn't travel along side walls. OP sensors show clear signals and provide a flame speed record. Flame speeds are low as are peak pressures. (41)
CH4/H2	0/100	10	***5***	0.50	-	100	-	0.143	0.153	130	No obstacles in duct. Target equivalence ratio is 0.5 Increased equivalence ratio from test 9. Stoichiometric condition and oxygen met satisfactorily. Useful data obtained although low equivalence and weak flame results in an absence of signals for the IPs suggesting flame front doesn't travel along side walls. OP sensors show clear signals and provide a flame speed record. Flame speeds are low as are peak pressures. (51)
CH4/H2	0/100	11	***3***	0.70	-	100	-	0.045	0.158	320	Change of Equivalence Ratio compared with test matrix - overpressure and flame speeds from test 9 and 10 low therefore E.R. changed from 0.3 to 0.7 No obstacles in duct. Target equivalence ratio is 0.7 Stoichiometric condition and oxygen met satisfactorily. Sensors show strong flame front progression on IPs and OPs. Peak pressure (0.3 bar) highest yet seen)
CH4/H2	40/60	12	***6***	0.85	40	60	-	0.102	0.152	280	No obstacles in duct. Target equivalence ratio is 1.0. Target equivalence ratio not fully reached for this mixture (60/40 H2/CH4). Oxygen met satisfactorily. Useful data obtained and stronger flame provides good flame speeds on both IP and OP sensors. Pressures consistent with other tests on this mixture at the same equivalence.
CH4/H2	40/60	13	**-**	0.35	40	60	-	0.04	0.15	43	**Test added to matrix to investigate EQRs nearer to 'real world conditions'.** No obstacles in duct. Target equivalence ratio is 0.35 Weakest equivalence tested for this mixture. Stoichiometric condition and oxygen met satisfactorily. Useful data obtained although low equivalence and weak flame results in an absence of signals for the IPs suggesting flame front doesn't travel along side walls. 3/4 of the OP sensors show clear signals and provide a flame speed record. Flame speeds are low as are peak pressures.

Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CO/H2	100/0	14	***17***	0.35	-	-	100	0.23	0.151		No Pressure readings No obstacles in duct. First test of pure CO injection. Mass flow condition met for CO. Due to dome valve pressure required to obtain CO mass flow, the oxygen dome pressure is at limit of operation and oxygen mass flow found to be oscillating. There is some evidence of ignition but test is not considered to provide useful data.
CO/H2	40/60	15	***21***	0.55	-	60	40	0.23	0.152		No clear readings Oxygen flow control valve not stabilising at 0.152 kg/s No obstacles in duct. Target equivalence ratio was 0.55 First test of H2/ CO injection (60/40). Mass flow condition met for CO but for oxygen, the mass flow shows instability for the same reasons as test 14 (dome valve pressure limit for oxygen). Sensor data on the IPs, OPs and pressure transmitters is absent but the thermocouples show a high temperature at the start of data collection (triggered on the igniter start). The conclusion is that pre-ignition has occurred for this mixture (despite the oxygen being below the 21% level).
CO/H2	40/60	16	***20***	0.50	-	60	40	0.23	0.152	91	Oxygen flow control valve not stabilising at 0.152 kg/s No obstacles in duct. Target equivalence ratio was 0.7 Further test of H2/ CO injection (60/40). Mass flow condition is not met for CO due to depleting reserve and for oxygen, a similar instability is showing for the same reasons as test 14 (dome valve pressure limit for oxygen). The resultant equivalence ratio is 0.5 for the mixture (but oxygen is indeterminate but above baseline exhaust value of 16.3%). Sensor data on the IPs is absent but OPs are showing a satisfactory signal indicating that the mixture ignited in the normal controlled way. The thermocouples also show initially low values which rise during the combustion event. Therefore no pre-ignition (autoignition) is in evidence for this test.
CO/H2	60/40	17	***20***	0.50	-	60	40	0.23	0.152	0.91	No obstacles in duct. Target equivalence ratio was 0.7 Continued testing of H2/ CO injection (60/40). Due to instability in the oxygen injection rate on previous tests due to the dome valve pressure being too close to its limit, the dome pressure for both control valves was reduced. The mass flow condition is now met for oxygen, but the lower available mixed gas pressure now limits the mass flow available for the fuel injection. This results in an effective equivalence ratio of 0.5, but with the correct oxygen make-up level. Sensor data on the IPs, OPs and pressure transmitters is absent but the thermocouples show a high temperature at the start of data collection (triggered on the igniter start). The conclusion is that pre-ignition has again occurred for this mixture.
CO/H2	60/40	18	***20***	0.50	-	60	40	0.23	0.152		No obstacles in duct. Target equivalence ratio is 0.7 RE-RUN OF TEST 17 TO CONFIRM AUTO-IGNITION. TEST ADDED TO MATRIX FOLLOWING AUTOIGNITION EVENT OF PREVIOUS TEST RESULTED IN ALMOST IDENTICAL OUTCOME. Note: due to auto-ignition all future tests with CO should allow for pre-triggering the data collection to 'catch' the autoignition event and subsequent pressure and flame speed data.Continued testing of H2/ CO injection (60/40). Due to instability in the oxygen injection rate due to the dome valve pressure being too close to its limit, the dome pressure for both control valves is reduced. The mass flow condition is now met for oxygen, but the lower available mixed gas pressure now limits the mass flow available for the fuel injection. This results in an effective equivalence ratio of the 0.5, but with the correct oxygen make-up level. Sensor data on the IPs, OPs and pressure transmitters is absent but the thermocouples show a high temperature at the start of data collection (triggered on the igniter start). The conclusion is that pre-ignition has again occurred for this mixture.
CH4/H2	40/60	19	**-**	0.35	40	60	-	0.038	0.152	75	**Test added to matrix to compare with tests on same mixtures of gas without congestion.** First of tests with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). Tests on mixture of 40% CH4 and 60% H2 with intent to start at low equivalence ratio (0.35) Experiment gave relatively weak flame speeds and overpressure but data set is satisfactory. Limited data set from IPs due to weak event but gave flame speeds consistent with those from OPs
CH4/H2	40/60	20	**-**	0.65	40	60	-	0.075	0.152	591	**Test added to matrix (as above)** Second test with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). Tests on mixture of 40% CH4 and 60% H2 at higher EQR Pressure transducers and optical probes provided reliable data showing significant increase in overpressure and some higher flame speeds which correlated well with data from ionisation probes. Highest overpressures yet recorded in any tests.
CH4/H2	40/60	21	***8***	0.85	40	60	-	0.102	0.152	1670	Third test with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). Tests on mixture of 40% CH4 and 60% H2 at highest EQR Pressure transducers and optical probes provided reliable data showing significant increase in overpressure and some higher flame speeds which correlated well with data from ionisation probes.

Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CH4/H2	0/100	22	***9***	0.30	0	100	-		0.152		Test with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). Very weak flame - only evidence being the rise of temperature on the gas thermocouples. No flame front signals present on the ionisation, optical or pressure sensors.
CH4/H2	0/100	23	***10***	0.40	0	100	-		0.152		Test with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). Very weak flame - only evidence being the rise of temperature on the gas thermocouples. No flame front signals present on the ionisation, optical or pressure sensors.
CH4/H2	0/100	24	***11***	0.50	0	100	-	0.017	0.155	318	Test with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). This 100% H2 test with higher equivalence ratio shows a more definite flame development and pressure signature. Optical probes give a clear flame velocity indication. The IPs carry more uncertainty with flame fronts being difficult to assign definite arival times in all cases. This gives more uncertainty about flame speeds derived from these sensors. Pressure shows growth in advance of the flame front arriving at the obstacle array at 6000mm and after arrival a pressure wave develops strongly in the downstream region. Some evidence of the pressure wave sharpening downstream of the obstacles. As noted for test 21, the some weak oscillation at 20 kHz shown on the downstream pressure sensors awaits further explanation.
CH4/H2	0/100	25	-	0.70	0	100	-	0.017	0.155	7620	**Test added to matrix to compare with test 11 (same EQR but without congestion)** Test with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). With highest equivalence ratio for pure H2, there is strong evidence of a rapid combustion and strong pressure wave development following flame impingement on the congestion region. Signals on most IPs and all OPs give a good indication of flame speed along the duct. These are in the region of 2000 - 2500 m/s. This case shows a step rise in flame speeds and associated pressures compared to the weaker mixtures so far tested. The peak pressures show a sharpening to shock behaviour downstream. The average pressure wave velocity between the last two sensors is 1818 m/s, which correspoonds to a predicted wave speed for the observed pressure pulse of 1703 m/s. The exit flame speed is 1724 m/s which suggests that this test case has given rise to a weak detonation wave event. As noted for test 21, the some weak oscillation at 20 kHz shown on the downstream pressure sensors awaits further explanation.
CH4/H2	0/100	26	-	0.60	0	100	-	0.017	0.155	1970	**Test added to matrix** Test with congestion in place. Eight (8) rows of congestion in place from central flange (between tube sections 2 and 3). This case represents an intermediate equivalence ratio for pure H2 to explore the region prior to the strong combustion event with equivalence of 0.7. There is clear evidence of a rapid combustion and a significant pressure wave development following flame impingement on the congestion region. Signals on most IPs and all OPs give a good indication of flame speed along the duct. These however are lower in the 200-300 m/s range. The peak pressures show a sharpening to shock behaviour downstream with a shock speed of around 900 m/s. The flame speed is much lower than this as shown for both IPs and OPs. As noted for test 21, the some weak oscillation at 20 kHz shown on the downstream pressure sensors awaits further explanation.
CH4/H2	0/100	27	***16***	0.50	0	100	-	0.017	0.155	1787	**First test with 15 rows of congestion** (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3 Pure hydrogen only starting at EQR 0.50 This case represents an intermediate equivalence ratio for pure H2 to compare with the same equivalence ratio with 8 congestion tubes in place, in anticipation of a stronger event. Most signals on the IPs and OPs provide flame arrival information, although there is some ambiguity for some positions leading to some uncertainty with the flame speed behaviour. The peak pressures show a sharpening after the congestion with a decrease in peak pressure towards the exit and a Mach number of around 1.25. The flame speed is much lower than this as shown for both IPs and OPs. As noted for other tests, where the pressure wave sharpens, the same weak oscillation at 20 kHz is shown on the downstream pressure sensors.
CH4/H2	0/100	28		0.40	0	100	-	0.017	0.155	461	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3 This case represents a lower equivalence ratio for pure H2 to compare with the same equivalence ratio with 8 congestion tubes in place. The combustion event provides poorly defined flame fronts with resulting absence of good signals on the IPs. The OPs provide some arrival information, and flame speeds.

Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CH4/H2	0/100	29		0.60	0	100	-	0.017	0.155	7159	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3 This case represents an increased equivalence ratio for pure H2 to compare with the same equivalence ratio with 8 congestion tubes in place. With this ratio and 15 rows of tube congestion, there is strong evidence of a rapid combustion and strong pressure wave development following flame impingement on the congestion region. Signals on most IPs and all OPs give a good indication of flame speed along the duct. These are in the region of 1660 - 1870 m/s. This case shows a step rise in flame speeds and associated pressures compared to the 0.4 and 0.5 equivalence ratio mixtures so far tested. The peak pressures show a sharpening to shock behaviour downstream. The average pressure wave velocity between the last two sensors is 1648 m/s. The exit flame speed is 1667 m/s which suggests that this test case has given rise to a weak detonation wave event. Further support for this comes from the observation that the pressure wave and flame front at the exit of the tube arrive within a single sampling interval of one another. As noted for test 21, the some weak oscillation at 20 kHz shown on the downstream pressure sensors awaits further explanation.
CH4/H2	40/60	30		0.55	40	60	-	0.062	0.149	284	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. Observation is that the combustion is a relatively weak event with this EQR based on peak pressures and flame speeds.
CH4/H2	40/60	30	1	0.55	40	60	-	0.062	0.149	284	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. Observation is that the combustion is a relatively weak event with this EQR based on peak pressures and flame speeds.
CH4/H2	40/60	31	2	0.65	40	60	-	0.0757	0.148	3016	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. Stronger combustion event compared with EQR of 0.55 as evidenced by peak pressure of 3 bar (vs 0.2 bar) and higher exit flame speed.
CH4/H2	40/60	32	-	0.60	40	60	-	-	-	-	Test not successful - DATA NOT PROCESSED
CH4	100	33	4	0.86	100	-	-	0.12	0.148	2620	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. A moderately strong combustion event at an EQR of 0.86 and showing a peak pressure of 2.6 bar. his should be contrasted with the corresponding pure methane case with no obstacles where the peak pressure was around 0.2 bar. Note that OP3 was later found to have loosened in its mounting, resulting in no signal for this sensor.
CH4	100	34	5	0.76	100	-	-	0.105	0.148	650	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. A weaker combustion event at an EQR of 0.76 and showing a peak pressure of 0.65 bar. This can be compared with the corresponding pure methane case with no obstacles where the peak pressure was around 0.2 bar.
CH4	100	35	6	0.65	100	-	-	0.089	0.147	300	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. A weak combustion event at an EQR of 0.65 and showing a peak pressure of 0.3 bar. This is comparable with the pure methane case with an EQR of 1 with no obstacles where the peak pressure was around 0.2 bar, giving an indication of the relation between incresing obstacles and decreasing EQR.
CH4/H2	60/40	36	10	0.65	60	40	-	0.0826	0.151	416	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. The first test of this new mixture. Combustion event is fairly weak with a peak pressure of 416 mbar. Prior to this test, the IPs sensor tips were treated to a blowtorch treatment raising them to yellow heat to attempt to remove any residual moisture. This was found in pre-checks to greatly improve their sharpness of performance. The results for this combustion test confirm this, with many more giving good flame transition signatures. The flame speeds are modest (~200 m/s at the exit) but it is also clear from th arrival times that the flame propagation is complex with arrival times at some of the locations being out of the expected sequence.
CH4/H2	60/40	37	11	0.75	60	40	-	0.096	0.155	1515	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the highest EQR used for this mixture. The combustion event is moderate in intensity with a peak pressure of 1500 mbar. Note that for this group of tests, the IPs sensor tips were treated to a blowtorch treatment raising them to yellow heat to attempt to remove any residual moisture. This was found in pre-checks to greatly improve their sharpness of performance. The results for this combustion test confirm this, with many more giving good flame transition signatures. The flame speeds are modest (~250 m/s at the exit) but there is also some evidence for this concentration that the flame propagation is complex with arrival times at some of the locations being out of the expected sequence. Flame speeds on the centreline are not always equal to the values measured with the wall sensors. The OPs provide an overall perspective across the tube diameter.

Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CH4/H2	60/40	38	12	0.60	60	40	-	0.075	0.148	363	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the lowest EQR used for this mixture. The combustion event is weak in intensity with a peak pressure of 363 mbar. Note that for this group of tests, the IPs sensor tips were treated to a blowtorch treatment raising them to yellow heat to attempt to remove any residual moisture. This was found in pre-checks to greatly improve their sharpness of performance. The results for this combustion test confirm this, with many more giving good flame transition signatures. The flame speeds are modest (~200 m/s at the exit) but there is also some evidence for this concentration that the flame propagation is complex with arrival times at some of the locations being out of the expected sequence. Flame speeds on the centreline are not always equal to the values measured with the wall sensors. For thi reason, the flame speeds based on the IPs are in two sets, one being based on the intervals between the wall sensors and the other based on the intervals between the array sensors within the body of the duct. The OPs provide an overall perspective across the tube diameter.
CH4/H2	40/60	39	3	0.61	40	60	-	0.07	0.154	600	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is an intermediate EQR for this mixture. The combustion event is weak in intensity with a peak pressure of 600 mbar. Note that for this group of tests, the IPs sensor tips were treated to a blowtorch treatment raising them to yellow heat to attempt to remove any residual moisture. This was found in pre-checks to greatly improve their sharpness of performance. It is noted that the IP signals carry more noise than usual making flame arrival difficult for some positions. The complexity of the flame propagation leads to some uncertainty in the calculation of this for some locatatons. However flame speeds are very modest (~100 -200 m/s). The OPs provide an overall perspective across the tube diameter, although OP3 at the exit does not rovide a signal. It is also noted that the photographic record did not show flame front emergence from the tube exit.
CH4/H2	40/60	40	extra	0.66	40	60	-	0.076	0.154	1353	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is a repeat of Test 31 and is the highest EQR tested for this 40/60 CH4/H2 mixture. By comparison this combustion event is relatively weak in intensity with a peak pressure of 1353 mbar compred previously with 3016 mbar. Note that for this group of tests, the IPs sensor tips were treated to a blowtorch treatment raising them to yellow heat to attempt to remove any residual moisture. This was found in pre-checks to greatly improve their sharpness of performance. It is noted however that the IP signals carry more noise than usual, making flame arrival difficult for some positions. The complexity of the flame propagation leads to some uncertainty in the calculation of this for some locatatons. The flame speeds are very modest (~100 -200 m/s) and the overall combustion event appears weaker that that for test 31. This is also confirmed by the absence of a flame on the exit OP3. It is also noted that the photographic record did not show flame front emergence from the tube exit. It should also be noted that the tdms file for this case contains two sets of data as this case was repeated during the data collection. The second data set shows very similar combustion behaviour, e.g. in terms of peak pressure and OP behaviour.
H2	100	41	extra	0.40	-	100	-	0.0235	0.148	0	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is lowest EQR value for the repeat tests with pure H2. The combustion has occurred on the evidence of the gas thermocouples. However the combustion is very weak and there is no evidence of a flame front propagating or of a pressure rise following ignition. No pressures or flame speeds are recorded for this case.
H2	100	42	7	0.50	-	100	-	0.0297	0.148	1400	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the intermediate EQR value for the repeat tests with pure H2. The combustion is of moderate strength and the IP signals are variable in their presence and relative order in tiime. The OP3 signal is weak and not included (to be investigated) and the velocity from these is consistent with that from the IPs in the region. The peak pressures is 1.4 bar and exit flame velocity is around 200 m/s
H2	100	43	8	0.60	-	100	-	0.0366	0.148	9400	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the highest EQR of the repeat tests pure H2. The combustion is strong and the IP signals are almost a complete set. Only two of the OPs have given a useful signal (to be investigated) and the velocity frrom these is consistent with that from the IPs in the region. The peak pressures (9.4 bar) and exit flame velocity (1666 m/s) indicated a detonation condition has been reached for this case.
H2	100	44	9	0.51	-	100	-	0.03	0.151	1762	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is an intermediate EQR using pure H2. The combustion is moderate and the IP and OP signals provide a basis for interpretation. All of the OP signals are present and velocities are generally consistent with those from the IPs at around 200m/s. The arrival times of flame fronts based on IP data suggests that flame development is complex with axis and wall sensors behaviing differently. The peak pressure is moderate at 1.7 bar.
CO	100	45	-	0.45	-	-	100	-	-	-	Test duplicated as test 46. There test data not processed

Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CO	100	46	19	0.44	-	-	100	0.359	0.15	130	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the first test of pure CO combustion but with a low EQR. The combustion is very weak and the IP and OP signals indicate low flame speeds (~ 100m/s). Some evidence of the flame weakening towards the exit of the duct (e.g. no signal on OP3). The peak pressures confirm a very weak event.
CO	100	47	20	0.60	-	-	100	0.51	0.159	574	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This represents an intermediate EQR using pure CO injection. The combustion is relatively weak and the IP and OP signals indicate moderate flame speeds (~200 - 300m/s). There is inconsistentency in velocity estimates among the IPs on axis and on the walls, suggesting complex flame development behaviour. The peak pressure is intermediate with that from adjacent EQR tests.
CO	100	48	21	0.77	-	-	100	0.7	0.152	3000	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the highest EQR value using pure CO combustion. The combustion is of modrate strength and the IP and OP signals indicate high flame speeds (up to 1000m/s). There is inconsistentency in velocity estimates among the IPs on axis and on the walls, suggesting complex flame development behaviour. It is noted that the flame signal on IP23 at the exit is effectively coincident in time with the shock wave arrival on K7 at the exit.
H2/CO	40/60	49	16	0.65	-	40	60	0.351	0.158	10380	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This test uses a 40/60 H2/CO mixture at a relatively high EQR. The combustion is very strong with very clear signals on both IPs and OPs. Exit flame speed is around 2000 m/s and the evidence is for the existence of a detonation where the pressure is high (10.3 bar) and the exit shock wave is coincident with the exit flame front.
H2/CO	40/60	50	17	0.41	-	40	60	0.209	0.17	227	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the first test of pure 40/60 H2/CO mixture combustion but with a low EQR. The combustion is very weak and the IP and OP signals are very incomplete. They indicate low flame speeds (~ 100m/s) but with considerable variability between axial and wall sensors. Some evidence of the flame weakening towards the exit of the duct (e.g. no signal on OP3). The peak pressure of 227 mbar confirms a very weak event.
H2/CO	40/60	51	-	0.50	-	40	60	-	-	-	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. PRE-IGNITION - DATA NOT PROCESSED
H2/CO	40/60	52	18	0.50	-	40	60	0.259	0.155	824	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is an intermediate EQR value using this H2/CO mixture. The combustion is trelatively weak with the OP signals indicate low flame speeds (~ 200m/s). IP signals are not strong and clear but generally confusing with no clear pattern of flame passage based on relative timings. The peak pressures of 824 mbar confirm a weak event.
H2/CO	60/40	53	13	0.40	-	60	40	0.142	0.19	218	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is the first test of the H2/CO mixture but with a low EQR. The combustion is very weak and the IP signals are mostly absent. Three OP signals indicate low flame speeds (~ 100m/s). The peak pressures confirm a very weak event.
H2/CO	60/40	54	14	0.50	-	60	40	0.183	0.175	1500	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This is an intermdiate test of the H2/CO mixture with a raised EQR. The combustion is rather very weak and the IP signals are of poor quality or absent. Four OP signals indicate low flame speeds (< 200m/s). The peak pressure is increased significantly compared with an EQR of 0.4 and is close to a likely industrial application limit.
H2/CO	60/40	55	-	0.55	-	60	40	-	-	-	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. PRE-IGNITION - DATA NOT PROCESSED
H2/CO	60/40	56	15	0.56	-	60	40	0.208	0.18	966	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This test represents a small increase in the previous EQR value usingthe 60 H2/40 CO mixture. This cautious increase was due to the large increase in peak pressure in moving from EQr 0.4 to EQr 0.5. However, the combustion in this case is weaker than expected and there is evidence of a (a) a weak pre-ignition giving a peak pressure of 200mbar followed 40msec later by (b) the main ignition giving a peak pressure of 1069 mbar. This main ignition occurs at the target mixture EQR of 0.56 but it appears that this is also an auto-ignition event. The peak pressure is lower than expected and and may be due to the exhaust mixture ahead of the flame front being depleted by the previous weak pre-ignition. The IP signals are of poor quality or absent. Three OP signals indicate low flame speeds (< 200m/s).
CH4/H2/CO	25/40/35	57	22	0.65	25	40	35	0.178	0.148	3128	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This test represents the first using a 3 component mixture of H2/CO/CH4 with an upper limit chosen for the EQR. The combustion in this case is of medium strength at a peak pressure of 3.12 bar. The OP signals indicate an exit flame speed of ~ 300m/s and the IPs generally agree. Differences remain in flame arrival times asssociated with the wall and centre of the duct.

Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CH4/H2/CO	25/40/35	58	23	0.56	25	40	35	0.147	0.148	1503	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This test represents a reduced value of EQR compared to the initial test with this 3 component mixture of H2/CO/CH4. The combustion in this weaker than that of the highest EQR with a peak pressure of 1.5 bar. The OP signals indicate an exit flame speed of 200-300m/s and the IPs generally agree. Differences remain in flame arrival times asssociated with the wall and centre of the duct.
CH4/H2/CO	25/40/35	59	24	0.51	25	40	35	0.133	0.148	1500	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This test represents a reduction in value of EQR to 0.51 from the previous value of 0.56 with the 3 component mixture of H2/CO/CH4. The combustion in fairly weak and it is noted that the peak pressure is similar to the that of the previous higher EQR value of 1.5 bar. The OP signals indicate an exit flame speed of 200- 300m/s and the IPs generally agree. Some of the OP and IP signals are missing indicating a weak event and differences remain in flame arrival times asssociated with the wall and centre of the duct.
CH4/H2/CO	25/40/35	60	extra	0.45	25	40	35	0.118	0.148	214	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3. This test represents the lowest value of EQR of 0.45 tested in order to confirm the lowest peak pressure likely to be achieved by this mixture of H2/CO/CH4. The combustion in very weak as indicated by the limited IP and OP signals. Flame speed is very low at ~100 m/s
H2	100	61	28	0.50	-	100	-	0.041	0.114	3890	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents the initial test with pure H2 at a lower exhaust temperature of 350 C (but with the same exhaust duct velocity) and using a modest EQR value of 0.5. The high temperature equivalent case for this condition produced a peak preaure of 1.76 bar. For this test the exit pressure, which is usually the highest, is 2.23 bar but it should be noted that the PCB transducer at position 3-6 indicates a much higher pressure of 9.7 bar. Multiple peaks associated with the PCB sensor raise the question as to whether 9.7 bar is correct. The time diference to the pressure wave arriving at the exit is around 2.5 msec, which would be too long for a wave associated with a 9.7 bar shock wave travelling at around 1600 m/s. A lower pressure value is therefore taken as representative as the peak pressure for this case (3.89 bar). The combustion is moderate in other respects with flame speeds around 200 m/s although it is noted that several sensors suggest much higher speeds in the region of the obstacle arrays of around 700 m/s.
H2	100	62	29	0.45	-	100	-	0.0326	0.128	788	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents an EQR reduced by 0.05 units from the initial test with pure H2 at the lower exhaust temperature of 350 C (but with the same exhaust duct velocity). The combustion is fairly weak with a peak pressure of 0.78 bar. The OPs indicate a flame speed in the range 150 - 200 m/s, however the IP sensors show very little evidence of a clearly defined flame front and no sensible flame speeds have been provided by these.
H2	100	63	30	0.35	-	100	-	0.0275	0.123	374	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents the lowest EQR value tested for pure H2 at the lower exhaust temperature of 350 C (but with the same exhaust duct velocity). The combustion is very weak with a peak pressure of 0.37 bar. The OPs indicate a flame speed in the range 150 - 200 m/s, however the IP sensors show very little evidence of a clearly defined flame front and no sensible flame speeds have been provided by these.
CH4/H2/CO	40/60/0	64	25	0.58	40	60	0	0.092	0.126	2774	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents the first test of the 60H2/40CH4 mixture at an upper EQR value and at the lower exhaust temperature of 350 C (but with the same exhaust duct velocity). The combustion is moderately strong with a peak pressure of 2.8 bar. A spurious noise spike has appeared within the data and upset the OP signals and the last two of the IPs. However there is evidence of elevated flame speeds within the middle section of the duct and the pressure signals are reproduced correctly.
CH4/H2/CO	40/60/0	65	26	0.50	40	60	0	0.0785	0.125	1579	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents an intermediate EQR value using the 60H2/40CH4 mixture and at the lower exhaust temperature of 350 C (but with the same exhaust duct velocity). The combustion is of medium strength with a peak pressure of 1.6 bar. Useful flame speed data is available from both OPs and IPs with these in the range up to 300 m/s, although some inconsistency exists between wall and centreline IP sensors.
CH4/H2/CO	40/60/0	66	27	0.40	40	60	0	0.0618	0.124	84	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents the lowest EQR value using the 60H2/40CH4 mixture and at the lower exhaust temperature of 350 C (but with the same exhaust duct velocity). The combustion is exremely weak with a peak pressure of only 0.08 bar. Usefully, the OPs provide flame arrival information at each station and this is very low at 50 - 90 m/s. The flame structure is not sufficiently sharp or intense to enable flame IP sensor signals.

Mixture	Mixture vol % ratio	Test Number	Test Matrix Ref.	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Peak Pressure mbar	Comments
CO/H2	60/40	67	extra	0.50	-	40	60	0.369	0.123	1087	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents an intermediate EQR value using the 40H2/60CO mixture and at the lower exhaust temperature of 350 C (but with the same exhaust duct velocity). The combustion is of modest strength with a peak pressure of only 1.1 bar. This pressure is 50% higher than the value obtained at the higher temperature and same EQR and this trend is consistent with the other low temperature results obtained with other gas mixtures. Usefully, the OPs provide flame arrival information at each station and this is in the 200 - 300 m/s range. The flame structure is not sufficiently sharp or intense to enable usefule flame speeds from the IP sensor signals and the relative timings of these suggest a complex flame development process.
CO/H2	60/40	68	extra	0.45	-	40	60	0.32	0.131	-	Test with 15 rows of congestion (row 8 on central flange with 7 rows projecting upstream into tube 2 and 7 rows projecting downstream into tube 3). This test represents an intermediate EQR value using the 40H2/60CO mixture and at the lower exhaust temperature of 350 C (but with the same exhaust duct velocity). EXTRA TEST. No further evaluation carried out.
H2	100	69	extra	0.50	-	40	-	0.111	0.472		TEST NOT CARRIED OUT - MASS FLOW FROM ENGINE NOT SYMETRICAL
H2	100	70	extra	0.50	-	100	-	0.111	0.472	183	High flow tests - 100% hydrogen at EQR 0.50 with all obstruction removed from circular duct. Successfully ignited. Weak event. Maximum overpressure 183 mbar and max. flame speed 197 m/s
H2	100	71	extra	0.45	-	100	-	0.098	0.472	173	High flow tests - 100% hydrogen at EQR 0.45 with all obstruction removed from circular duct. Successfully ignited. Weak event. Maximum overpressure 173 mbar and max. flame speed 266 m/s
H2/CH4	40/60	72	extra	0.70	60	40	-	0.333	0.472	359	High flow tests - 1st test with 60% methane and 40% hydrogen at EQR 0.70 with all obstruction removed from circular duct. Successfully ignited. Moderately weak event. Maximum overpressure 359 mbar and max. flame speed 394 m/s
H2/CH4	40/60	73	extra	0.65	60	40	-	0.307	0.472	238	High flow tests - 2nd test with 60% methane and 40% hydrogen at EQR 0.65 with all obstruction removed from circular duct. Successfully ignited. Moderately weak event. Maximum overpressure 238 mbar and max. flame speed 264 m/s