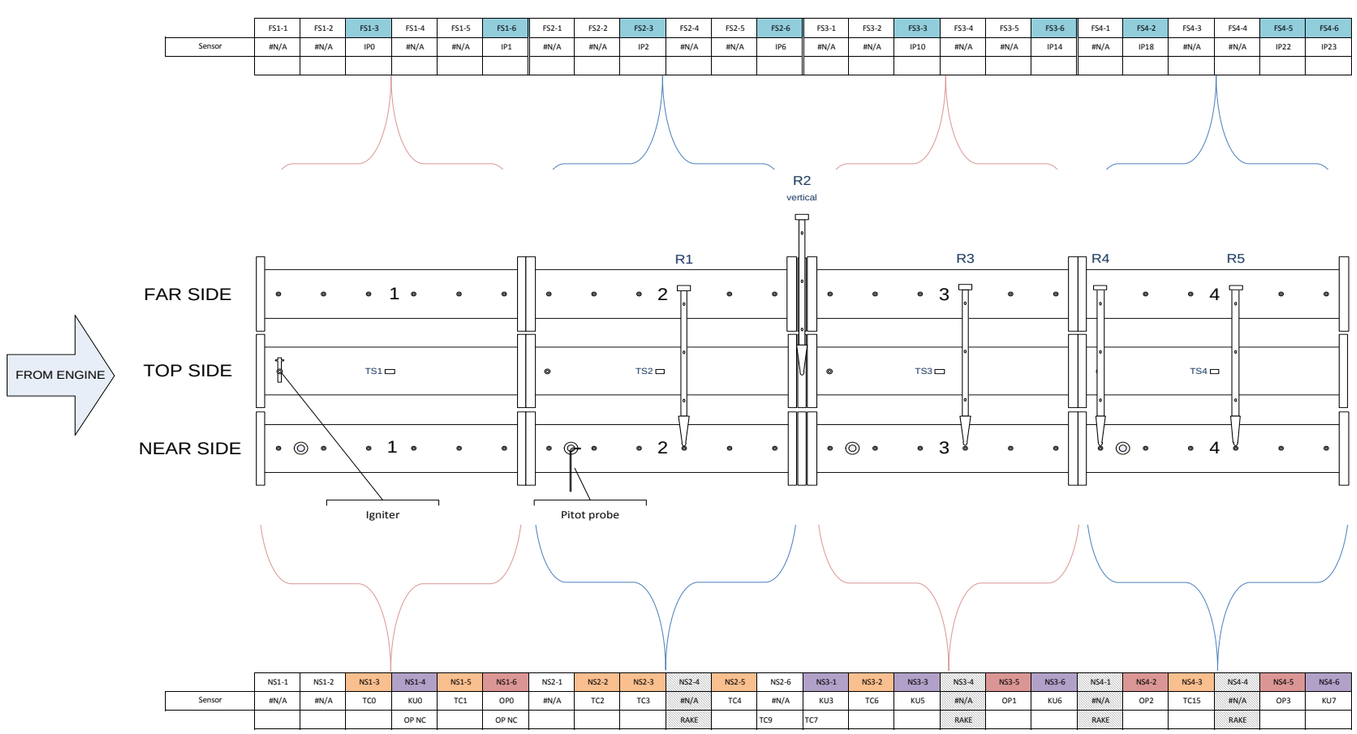
Mixture	Mixture vol % ratio	Test Number	***Test Matrix Ref.***	Eq. Ratio	CH4 vol%	H2 vol%	CO vol%	Fuel Gas Flow Rate [kg/s]	Oxygen Flow Rate [kg/s]	Comments
CH4/H2	100/0	1	***1***	1.00	100	-	-		0.152	1 No obstacles in duct. Pure methane starting test mixture. Stoichiometric condition and oxygen met satisfactorily, 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	-	-		0.152	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	-	-		0.152	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	-	-		0.152	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	-		0.152	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	-		0.152	**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	-		0.152	**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	-	0.152	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	-	0.152	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	-	0.152	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	-	0.152	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	-	0.152	**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.
CO/H2	100/0	14	***17***	0.35	-	-	100	0.152	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	0.152	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	0.152	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		17	***20***	0.50	-	60	40	0.152	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		18	***20***	0.50	-	60	40	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.



	FS1-1	FS1-2	FS1-3	FS1-4	FS1-5	FS1-6	FS2-1	FS2-2	FS2-3	FS2-4	FS2-5	FS2-6	FS3-1	FS3-2	FS3-3	FS3-4	FS3-5	FS3-6	FS4-1	FS4-2	FS4-3	FS4-4	FS4-5	FS4-6
Sensor	#N/A	#N/A	IP0	#N/A	#N/A	IP1	#N/A	#N/A	IP2	#N/A	#N/A	IP6	#N/A	#N/A	IP10	#N/A	#N/A	IP14	#N/A	IP18	#N/A	#N/A	IP22	IP23

	NS1-1	NS1-2	NS1-3	NS1-4	NS1-5	NS1-6	NS2-1	NS2-2	NS2-3	NS2-4	NS2-5	NS2-6	NS3-1	NS3-2	NS3-3	NS3-4	NS3-5	NS3-6	NS4-1	NS4-2	NS4-3	NS4-4	NS4-5	NS4-6
Sensor	#N/A	#N/A	TC0	KU0	TC1	OP0	#N/A	TC2	TC3	#N/A	TC4	#N/A	KU3	TC6	KU5	#N/A	OP1	KU6	#N/A	OP2	TC15	#N/A	OP3	KU7
				OP NC		OP NC				RAKE		TC9	TC7			RAKE			RAKE			RAKE		

Ionisation Probe
Pressure Transducer
Thermocouple
Optical Probe

Further Instrumentation		
Location	Sensor	Working
TS1-1	TC8	
TS2-1	TC10	
TS3-1	TC12	
TS4-1	TC14	
R1-1	IP3	
R1-2	IP4	
R1-3	IP5	
R2-1	#N/A	
R2-2	#N/A	
R2-3	#N/A	
R3-1	IP11	
R3-2	IP12	
R3-3	IP13	
R4-1	IP15	
R4-2	IP16	
R4-3	IP17	
R5-1	IP19	
R5-2	IP20	
R5-3	IP21	
KU3	TC7	
KU4	TC9	
KU6	TC13	
pitot	TC11	

Item	Location	DAQ	Channel	Measurement	Instrument	Supplier	Range	Signal	Excitation	S/R
IP0	FS1-3	PXIe	PXI Slot2/ai0	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP1	FS1-6	PXIe	PXI Slot2/ai1	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP2	FS2-3	PXIe	PXI Slot2/ai2	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP3	R1-1	PXIe	PXI Slot2/ai3	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP4	R1-2	PXIe	PXI Slot2/ai4	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP5	R1-3	PXIe	PXI Slot2/ai5	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP6	FS2-6	PXIe	PXI Slot2/ai6	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP7		PXIe	PXI Slot2/ai7	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP8		PXIe	PXI Slot6/ai0	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP9		PXIe	PXI Slot6/ai1	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP10	FS3-3	PXIe	PXI Slot6/ai2	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP11	R3-1	PXIe	PXI Slot6/ai3	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP12	R3-2	PXIe	PXI Slot6/ai4	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP13	R3-3	PXIe	PXI Slot6/ai5	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP14	FS3-6	PXIe	PXI Slot6/ai6	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP15	R4-1	PXIe	PXI Slot6/ai7	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP16	R4-2	PXIe	PXI Slot7/ai0	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP17	R4-3	PXIe	PXI Slot7/ai1	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP18	FS4-2	PXIe	PXI Slot7/ai2	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP19	R5-1	PXIe	PXI Slot7/ai3	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP20	R5-2	PXIe	PXI Slot7/ai4	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP21	R5-3	PXIe	PXI Slot7/ai5	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP22	FS4-5		PXI Slot7/ai6	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
IP23	FS4-6	PXIe	PXI Slot7/ai7	Flame Presence	Ionisation Probe	Bruce Ewan	TBC	-5 to 5V	60V	100 kHz
OP0	NS1-6	PXIe	PXI1Slot4/ai0	Flame Presence	Optical Probe	Bruce Ewan	TBC	-5 to 5V	30V	100 kHz
OP1	NS3-5	PXIe	PXI1Slot4/ai1	Flame Presence	Optical Probe	Bruce Ewan	TBC	-5 to 5V	30V	100 kHz
OP2	NS4-2	PXIe	PXI1Slot4/ai2	Flame Presence	Optical Probe	Bruce Ewan	TBC	-5 to 5V	30V	100 kHz
OP3	NS4-5	PXIe	PXI1Slot4/ai3	Flame Presence	Optical Probe	Bruce Ewan	TBC	-5 to 5V	30V	100 kHz
OP4		PXIe	PXI1Slot4/ai4	Flame Presence	Optical Probe	Bruce Ewan	TBC	-5 to 5V	30V	100 kHz
OP5		PXIe	PXI1Slot4/ai5	Flame Presence	Optical Probe	Bruce Ewan	TBC	-5 to 5V	30V	100 kHz
TC0	NS1-3	PXIe	SC1Mod4/ai0	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC1	NS1-5	PXIe	SC1Mod4/ai1	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC2	NS2-2	PXIe	SC1Mod4/ai2	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC3	NS2-3	PXIe	SC1Mod4/ai3	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC4	NS2-5	PXIe	SC1Mod4/ai4	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC5		PXIe	SC1Mod4/ai5	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC6	NS3-2	PXIe	SC1Mod4/ai6	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC7	KU3	PXIe	SC1Mod4/ai7	Gas Temperature (Wall)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC8	TS1-1	PXIe	SC1Mod4/ai8	Temperature (surface)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC9	KU4	PXIe	SC1Mod4/ai9	Temperature (kulite body)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC10	TS2-1	PXIe	SC1Mod4/ai10	Temperature (surface)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC11	pitot	PXIe	SC1Mod4/ai11	Temperature (kulite body)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC12	TS3-1	PXIe	SC1Mod4/ai12	Temperature (surface)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC13	KU6	PXIe	SC1Mod4/ai13	Temperature (kulite body)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC14	TS4-1	PXIe	SC1Mod4/ai14	Temperature (surface)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
TC15	NS4-3	PXIe	SC1Mod4/ai15	Temperature (pitot)	K-Type Thermocouple	TC-Direct	1100°C	Conditioned	None	5 kHz
KU0	NS1-4	PXIe	SC1Mod1/ai0	Pressure		Kulite				100 kHz
KU1		PXIe	SC1Mod1/ai1	Pressure		Kulite				100 kHz
KU2		PXIe	SC1Mod1/ai2	Pressure	XTEH-10L-190M-50BARA	Kulite		0-100 mV		100 kHz
KU3	NS3-1	PXIe	SC1Mod1/ai3	Pressure		Kulite				100 kHz
KU4		PXIe	SC1Mod1/ai4	Pressure		Kulite				100 kHz
KU5	NS3-3	PXIe	SC1Mod1/ai5	Pressure		Kulite				100 kHz
KU6	NS3-6	PXIe	SC1Mod1/ai6	Pressure		Kulite				100 kHz
KU7	NS4-6	PXIe	SC1Mod1/ai7	Pressure		Kulite				100 kHz
PB1		PXIe	PXI Slot3/ai0	Pressure	113824	PCB	68 bar	0-5 V	20-30 V	1 MHz
PB2		PXIe		Pressure	113825	PCB	68 bar	0-5 V	20-30 V	1 MHz

Date	13 August 2014
Time	14:03
Test Number	3
Mixture Composition	100% methane
Ambient Temperature	14
Ambient Pressure	957
Wind Speed	5 m/s
Wind direction	W
Relative Humidity	92.00%
Equivalence Ratio	1.00

General Comments: (weather, rig configuration)

Weather: Overcast with occassional sunny spells. Light breeze from the West.

Tube configuration:

4 x 3m tube sections
uncongested
igniter 250mm from beginning of tube section

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.

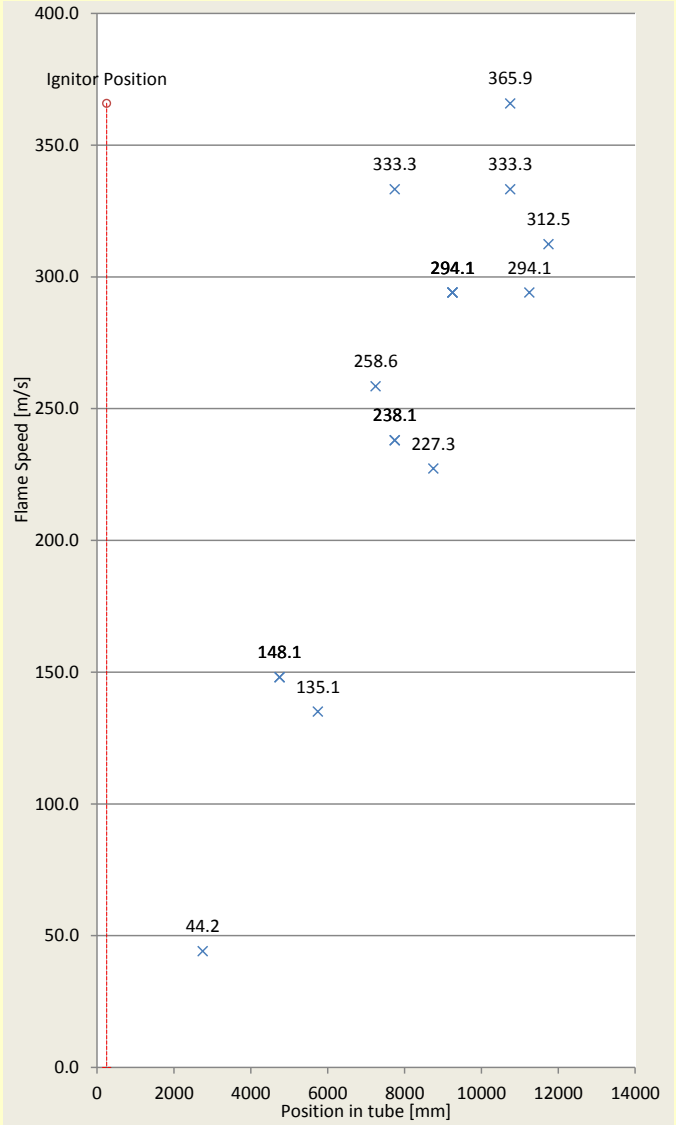
Headlines

Max overpressure	Max. flame speed	Max. temperature
209 mbar	366 m/s [ionisation probes]	1165 °C
	312 m/s [optical probes]	

Location of igniter	250	mm	Time of ignition	1.1638	seconds

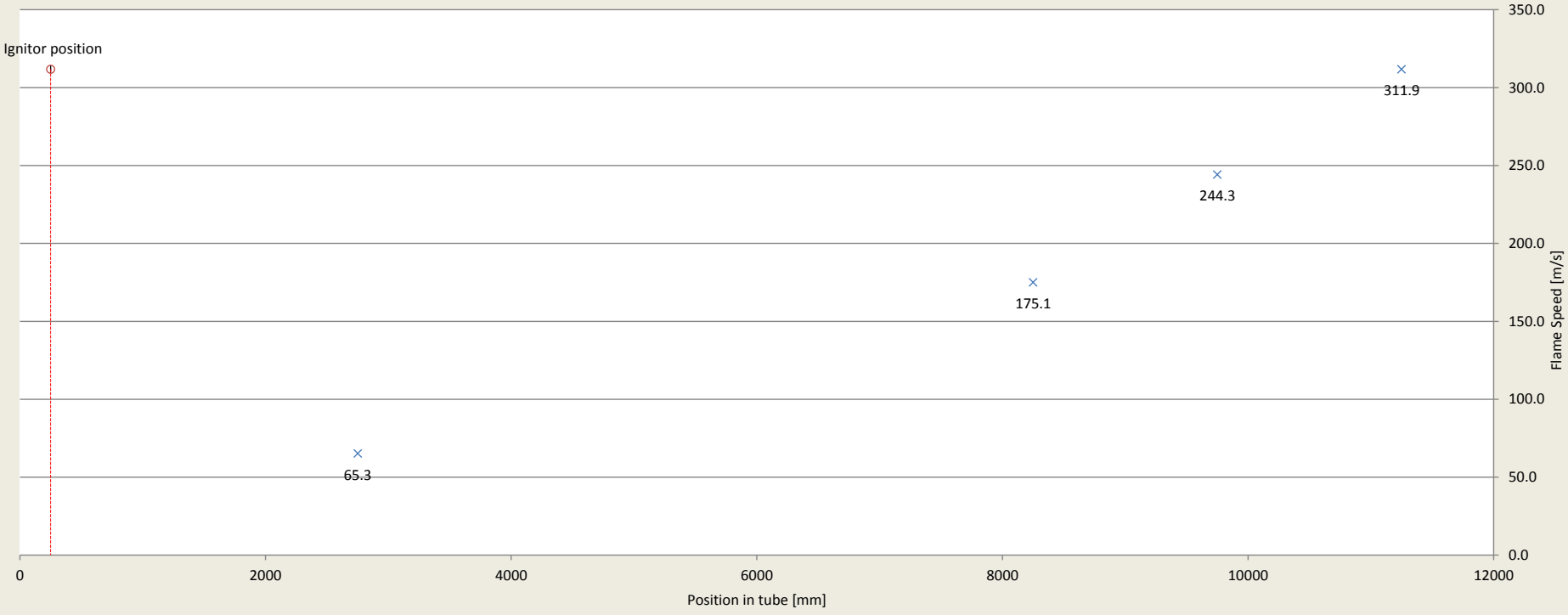
IP Number	Location label	Data Name	Position in tube (mm)	Flame arrival time (s)	Avg Flame speed from last sensor (m/s)
REF	#N/A	Flameion_0	#N/A	1.1907	
IP1	FS1-6	Flameion_1	2750	1.2020	44.2
IP2	FS2-3	Flameion_2	4250	NS	
IP3	R1-1	Flameion_3	4750	1.2155	148.1
IP4	R1-2	Flameion_4	4750	1.2155	148.1
IP5	R1-3	Flameion_5	4750	NS	
IP6	FS2-6	Flameion_6	5750	1.2229	135.1
IP7	0	Flameion_7	#N/A	NS	
IP8	0	Flameion_8	#N/A	NS	
IP9	0	Flameion_9	#N/A	NS	
IP10	FS3-3	Flameion_10	7250	1.2287	258.6
IP11	R3-1	Flameion_11	7750	1.2308	238.1
IP12	R3-2	Flameion_12	7750	1.2302	333.3
IP13	R3-3	Flameion_13	7750	1.2308	238.1
IP14	FS3-6	Flameion_14	8750	1.2352	227.3
IP15	R4-1	Flameion_15	9250	1.2375	294.1
IP16	R4-2	Flameion_16	9250	1.2375	294.1
IP17	R4-3	Flameion_17	9250	1.2375	294.1
IP18	FS4-2	Flameion_18	9750	NS	
IP19	R5-1	Flameion_19	10750	1.2420	333.3
IP20	R5-2	Flameion_20	10750	1.2416	365.9
IP21	R5-3	Flameion_21	10750	NS	
IP22	FS4-5	Flameion_22	11250	1.2437	294.1
IP23	FS4-6	Flameion_23	11750	1.2453	312.5

365.9



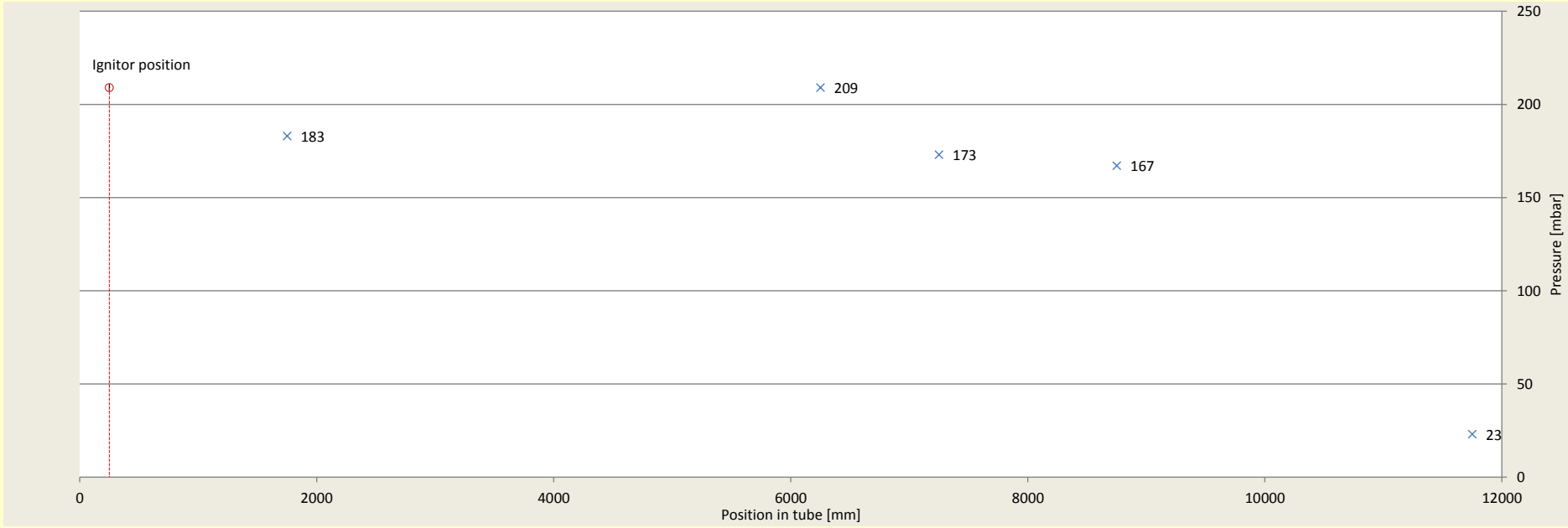
Location of igniter	250	mm	Time of ignition	1.16353	seconds

OP Number	Location label	Position in tube (mm)	Flame arrival time (s)	Average flame speed (m/s)
OP0	NS1-6	2750	1.20183	65.3
OP1	NS3-5	8250	1.23324	175.1
OP2	NS4-2	9750	1.23938	244.3
OP3	NS4-5	11250	1.24419	311.9
OP4	0	#N/A		
OP5	0	#N/A		



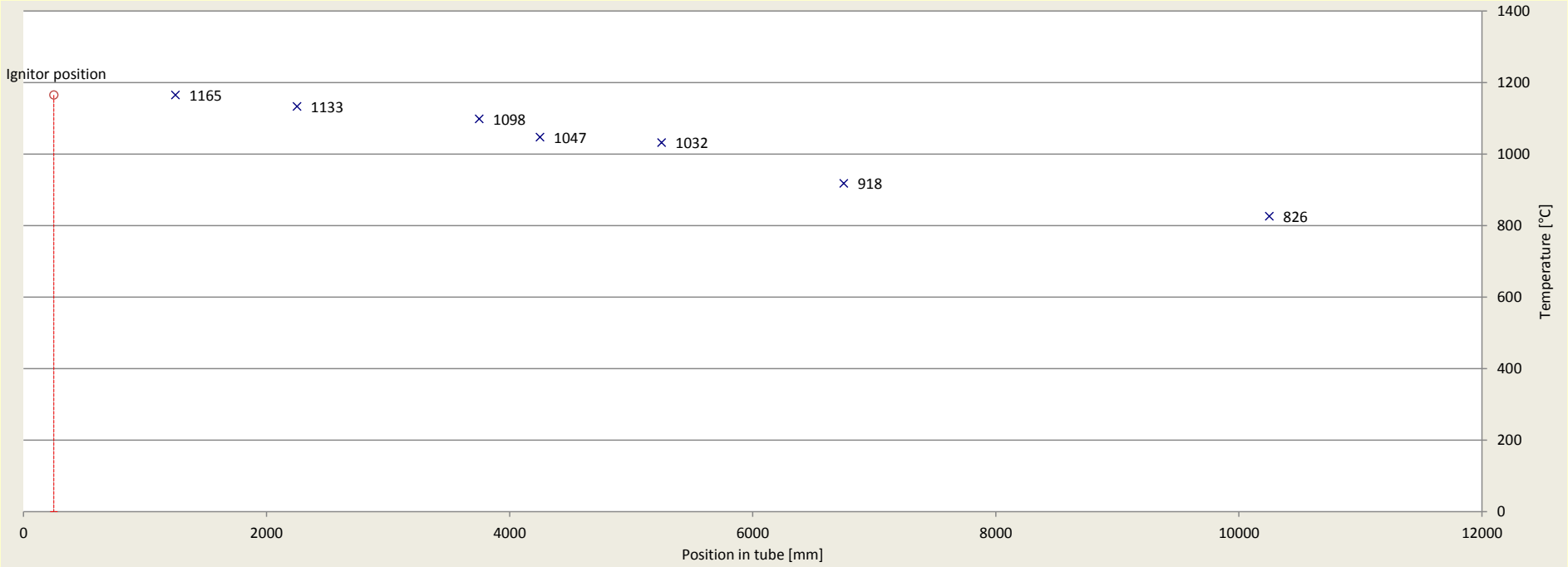
Location of igniter 250 mm

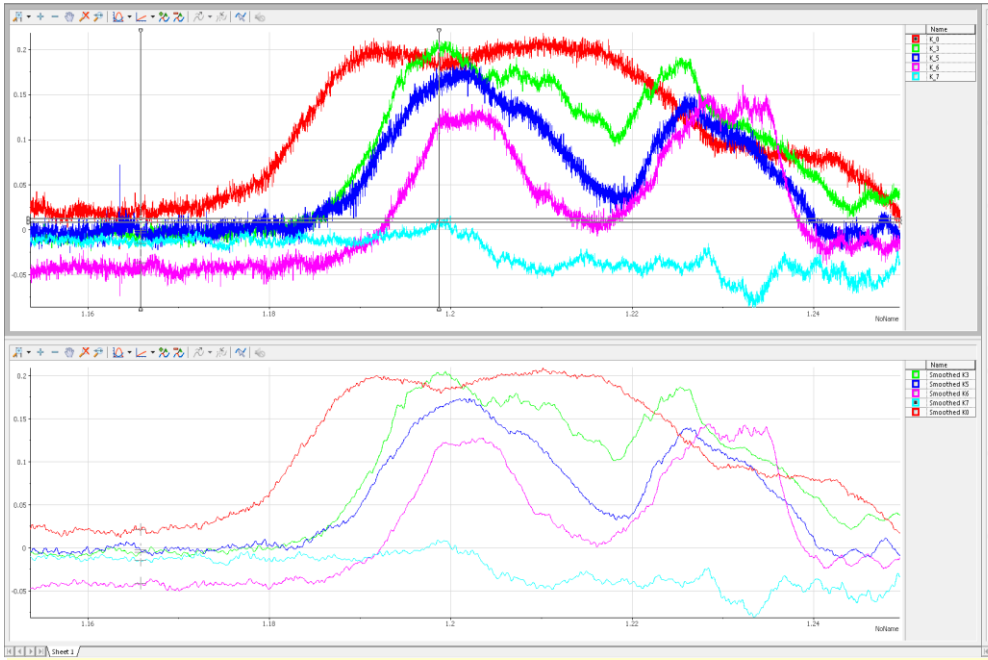
Transducer number	Location	Position in tube [mm]	ΔPmax [mbar]
KU0	NS1-4	1750	183
KU1	0	#N/A	
KU2	0	#N/A	
KU3	NS3-1	6250	209
KU4	0	#N/A	
KU5	NS3-3	7250	173
KU6	NS3-6	8750	167
KU7	NS4-6	11750	23



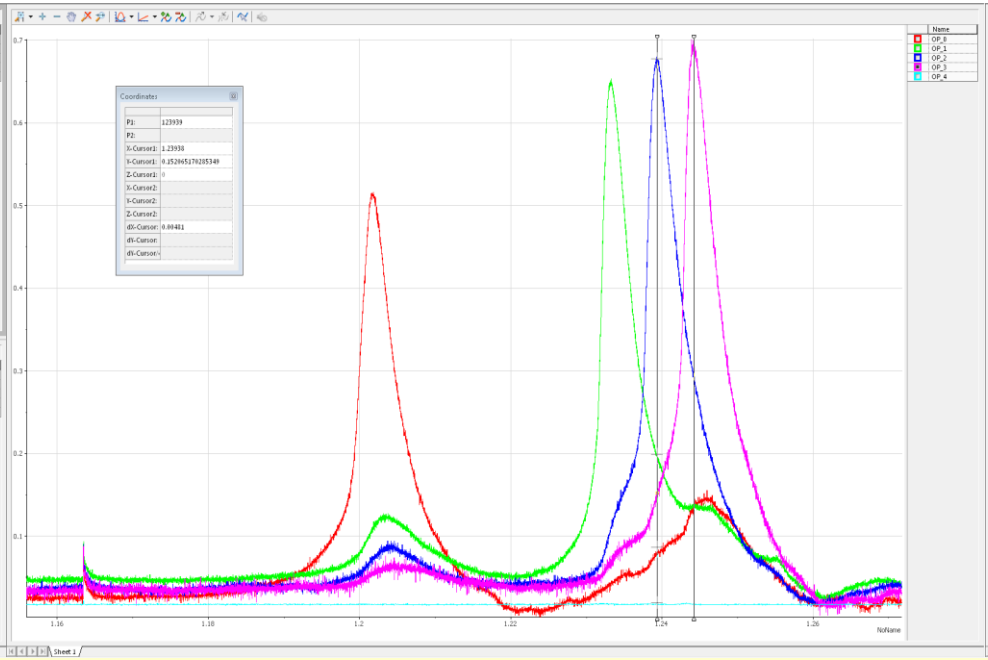
Location of igniter 250 mm

Thermocouple number	Location	Position in tube (mm)	T_{max} (deg C)
TC0	NS1-3	1250	1165
TC1	NS1-5	2250	1133
TC2	NS2-2	3750	1098
TC3	NS2-3	4250	1047
TC4	NS2-5	5250	1032
TC5	0	#N/A	
TC6	NS3-2	6750	918
TC15	NS4-3	10250	826

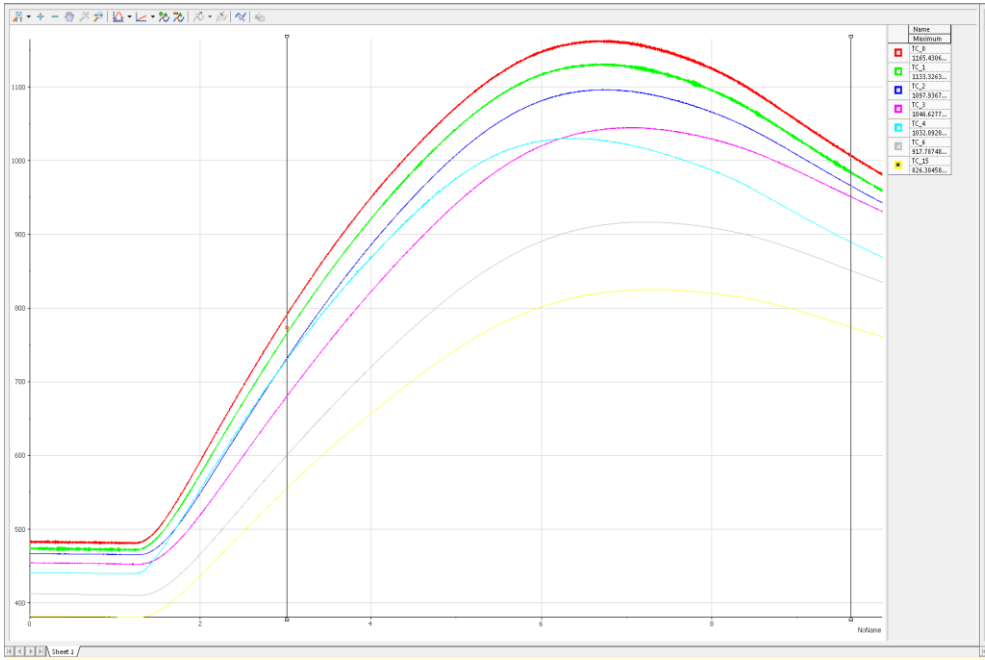




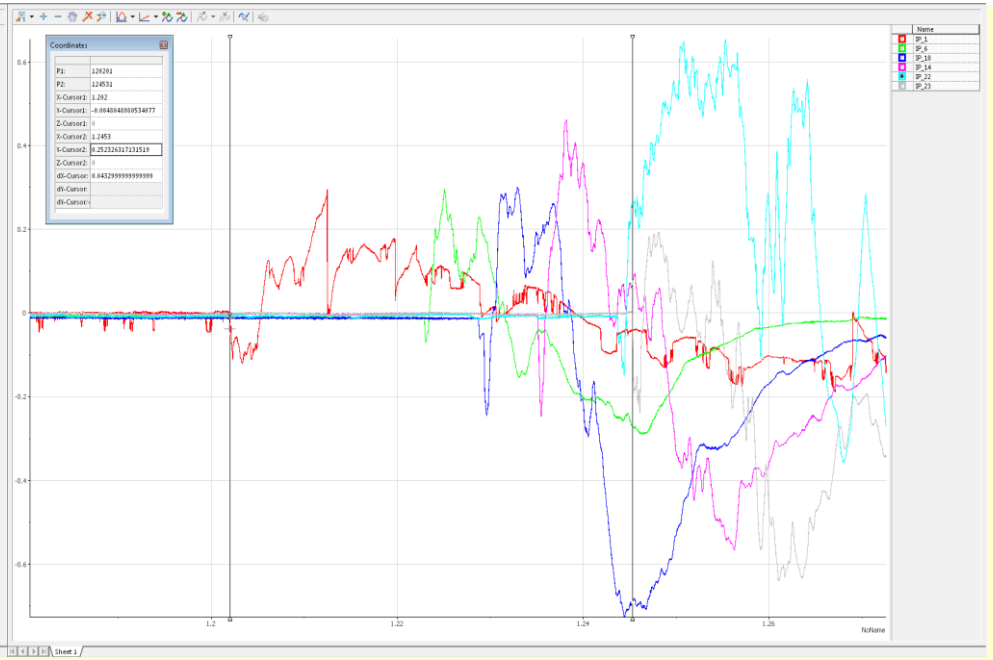
Pressure



Optical



Temperature



Ionisation Probes (Wall)