



Joint Industry Programme on carbon monoxide issues

Experimental work to study the interaction
between air extraction equipment and
open-flued appliances - Phase 1

Prepared by
Advantica Technologies Limited
(formerly BG Technology)
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The results of full-scale experiments are reported to determine the effect of extract fans on open flued gas appliances. Three types of gas appliance (a gas fire, a central heating boiler, and a combi boiler) and two type of extractor (window mounted, and cooker hood) were used. Two different ventilator heights were also used.

Tests were carried out with different extract rates, and with both initially cold and hot flues. The extraction rate was increased until a reversed flow in the flue could be maintained. Temperatures in the room containing the appliance were measured. Concentrations of carbon monoxide, carbon dioxide and oxygen were monitored at several heights in different rooms of the experimental house facility, and also close to the boiler, and in the air extract system.

During the final part of the test the ventilator was gradually opened from the minimum size recommended by the appropriate British Standard until the flue pulled normally.

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SUMMARY

INTRODUCTION

The effective removal of combustion products through the flue of an open-flued gas appliance can be affected by a number of processes, e.g. blockage of the flue or inadequate ventilator air provision to the appliance. The operation of air extraction equipment in a property can also cause the combustion products to be inefficiently removed by depressurising the area within which the appliance is located and offering a preferred pathway into the property.

This report describes work carried out to determine what factors contribute to this process in a full scale domestic property, and produces some guidelines for the installers of gas appliances and extract fans.

METHODOLOGY

A programme of work was carried out in a full scale brick built house using 3 types of open-flued gas appliance. Extract rates, gas concentrations, temperatures, and pressures were monitored during the tests.

RESULTS

- a) Flue reversal can be obtained in the Gas Fire and Central Heating boiler using low ($90\text{m}^3/\text{hr}$) extraction rates. Higher extraction rates were required with the Combi boiler to produce flue reversal.
- b) The rate of production of carbon monoxide was dependent on the appliance. Larger quantities were produced at higher (>math>200\text{m}^3/\text{hr}</math>) extraction rates.
- c) Closure of an intervening door between the appliance and the extract system caused dramatic / significant increases in the quantity of carbon monoxide produced by the Combi and Central Heating Boilers respectively.
- d) The temperature rise alone, compared to normal operation of the appliances, would be unlikely to warn an occupant of a problem.
- e) A linear relationship (with some scatter) was seen between the extra ventilator area required to make the flue revert to normal flow and the excess extraction rate

(The excess extraction rate is defined as
flow rate used - flow rate required to just reverse the cold flue)

- f) In all the tests the extra ventilator area required to make a reversed flue flow normally was greater than 50cm^2

CONCLUSIONS

Any further work should cover a wider range of appliances. Examples of items to be included are:-

- Low level extractors (e.g. tumble driers)
- Different designs of draught diverters on types of appliance already tested
- Different types of appliances (e.g. flame effect gas fires)

1 INTRODUCTION

Open-flued appliances work by taking air for combustion from the volume surrounding the appliance, and venting the combustion products via the flue to the atmosphere. If the process of venting is impeded, e.g. by an adverse flow in the flue, unwanted combustion products can be spilled into the volume around the appliance. Whilst current legislation requires anti-vitiation devices to be fitted to new appliances, a substantial population of older appliances (up to 40 million altogether) currently installed in the UK includes a significant number without such safety features. The anti-vitiation devices fitted to new appliances may also not work effectively under such conditions.

Open-flued appliances are designed with a draught diverter to cope with intermittent downdraught in the flue (caused generally by wind effects around the flue terminal) to ensure the products of combustion do not directly affect the appliance burners. However for these short periods the combustion products enter the room by the draught diverter, rather than being evacuated by the flue.

A potential way of producing adverse flow in the flue is the operation of an extraction fan near the open-flued appliance. This causes de-pressurisation of the room and consequently air from outside may flow down the flue into the room, causing the combustion products to be spilled into the room. Examples of appliances with extraction fans are cooker hoods, tumble driers, fan assisted open-flued appliances, as well as wall / window mounted extraction fans themselves.

The work used three different types of appliance, and looked at the effect of the type and location of the extract fan, and the position of a ventilator (sized to comply with BS5440^{#1} minimum requirements on area). At the end of a typical experiment the extract fan was left on and the extra ventilator area necessary to allow normal operation of the flue was determined.

2 EXPERIMENTAL FACILITIES

2.1 THE TEST ENCLOSURE

The programme of experiments was carried out in the Ventilation Test House facility at the BG Technology Fauld Test Site. This test facility is a purpose-built two-storey detached house of standard brick cavity wall construction, with a pitched tiled roof (see Figure 1). The upper and lower floors each have dimensions of approximately 5.7m x 5.7m x 2.3m high and are connected by a staircase. Both the upper and lower floors have been subdivided into connecting rooms by installing standard internal partition walls. Doorways were located in these partitions and doors fitted. (The dimensions of the internal interconnecting doorways are 1.98m x 0.78m). The layout of the ground and first floor is shown in Figure 2.

The lower floor was raised above ground level to provide an under floor void of approximate dimensions 5.7m x 5.7m x 0.9m. This was normally ventilated but the ventilators and access openings were blocked off for this study to provide an unventilated void.

The house had one entrance door and twenty-nine windows. The number and locations of the windows are such that when the upper and lower floors were subdivided, all rooms contained at least two windows on different walls. This arrangement allowed a wide range of ventilation regimes to be investigated. Ventilation was available within a room via openings of adjustable area at high level (located in the upper portion of a window, 1.93m from the floor) and/or at low level (0.38m from the floor). The positions of the ventilators are shown in Figure 3. In all tests Door D was closed and the top, bottom and sides were sealed with tape. Doors not directly into the rooms used in a particular test were closed, but not sealed. The door(s) directly into these rooms were sealed by tape, except as stated in Table 3.

The gas appliances and extract fans were located on the ground floor of the test house facility (see Figure 2) during this test programme. The positions used are shown in Figure 3 and details of the configuration used for each test are described under the test details.

2.2 GAS APPLIANCES

The gas appliances used were a floor standing box radiant gas fire, a wall-mounted central heating boiler, and a wall-mounted combi-boiler. Details of these appliances are presented below. The locations of the appliances are shown in Figure 3.

2.2.1 Gas fire

This floor standing appliance was a Cannon K26 Misermatic box radiant gas fire with a maximum heat input of 6.45kW. The fire was mounted in a Firebox and flued by 125mm diameter twin walled flue. The flue was terminated in the loft space, and had a length of approximately 5 metres. (To make the flue pull less susceptible to the effects of wind conditions, the flue was terminated in the loft space. There was no evidence of any combustion product build up in the loft space influencing the experiments.)

2.2.2 Combi-boiler

The wall-mounted combi-boiler was a Vaillant VCW GB 280H model with a maximum heat input of 35.4kW (120,800Btu/hr). The appliance was supported on a trolley and was located at a height of 0.95m from the floor, with the back of the boiler approximately 0.2m from the wall. The appliance was flued by 125mm diameter twin walled flue which terminated in the loft space, and had a length of approximately 3½ metres.

2.2.3 Central heating boiler

The wall-mounted central heating boiler was a Myson Apollo 40C model with a maximum heat input of 15.4kW (52,600Btu/hr). It was supported on a trolley and located at a height of 1.23m from the floor, with the back of the boiler approximately 0.1m from the wall. The appliance was flued by 100mm diameter twin walled flue which terminated in the loft space, and had a length of approximately 3½ metres.

2.2.4 Operating arrangements

The gas fire did not have a thermostat installed and, following ignition, was operated continuously at the maximum heat output setting.

The Combi-boiler, and Central Heating boiler were operated continuously (at maximum heat output) by ensuring a constant flow of water was passing through them. In this way, the water outlet temperature was prevented from becoming high enough to cause the appliance to turn off or cycle. The hot water produced was taken via a flexible hose and disposed of outside the building.

2.3 GAS SUPPLY

Natural gas was supplied to the appliances from high pressure cylinders (approximately 120bar cylinder pressure). The cylinder pressure was reduced using a two-stage pressure reduction system based upon a Fisher 1301F inlet regulator followed by a Fisher 630-312 governor. The outlet pressure of the two-stage pressure reduction system was adjusted to approximately 0.3bar. Gas was then delivered to the Test House through 40mm internal diameter pipe work via a bank of rotameters, which could be used to visually monitor the gas flow rate to an appliance during an experiment, and a further governor to reduce the supply pressure to the house to about 35mbar. The 40mm internal diameter supply pipe was connected to a 25mm internal diameter riser in the void beneath the Test House, which passed through the floor of the lower storey and then to the gas meter inlet via a short length of flexible pipe work. The meter governor was set to provide an outlet pressure of approximately 20mbar which is typical of a domestic system. The meter outlet was connected to a 15mm internal diameter copper pipe installed around the walls of the lower storey of the Test House approximately 10cm above floor level. The gas appliances were supplied from this copper carcassing by a flexible hose.

2.4 AIR EXTRACTION EQUIPMENT

A schematic diagram of the air extraction system is shown in Figure 4. The air extraction system consisted of 2 Xpelair Centrifugal Duct fans, type XID 150, a flow measurement section using a Trox VMR125 and a Furness Controls micromanometer, type FCS300, and 150mm diameter flexible ducting. The outlet from the system was positioned so that combustion products did not re-enter the house. The inlet from the room was via an adapter plate which could be fitted in place of the top section of one of the windows of the house. This was moved to the appropriate window for the test.

The Cooker Hood was a Stoves 029, connected to the normal inlet via 125mm ducting.

Flow was measured via the Trox VMR125, and could be adjusted by using a Variac to control the speed of the fans.

2.5 EXPERIMENTAL MEASUREMENTS

During each experiment, measurements were made to monitor the following parameters:-

- a) Concentration of carbon monoxide, carbon dioxide and oxygen present within the test enclosure, in the combustion air supply to the appliance, and in the draught diverter, and in the flue;
- b) Temperatures within the test enclosure, the draught diverter, and the flue;
- c) Pressures in the test enclosure and the flue;
- d) Prevailing weather conditions outside the Test House.

Details of these measurements are outlined below.

2.5.1 Infrared analysers

The concentration of carbon monoxide, carbon dioxide and oxygen within the rooms of the test enclosure was monitored by means of sample probes attached to a sample stand. The position of these stands is shown on Figure 3. The stand in the centre of the room containing the gas appliance supported seven probes installed to provide measurements of gas concentration on a vertical axis over essentially the full height of the room between floor and ceiling level. The remaining stands supported six sample probes. In addition sample probes were located in the path of the combustion air supply to the appliance, the draught diverter and the flue, and in the ductwork from the extract fan. The heights of the sample probes above the ground floor are given in Table 1.

The probes were sampled in the required sequence using a stream selection unit controlled by the data logging/analysis system. Three analysers were used. The sample probe sequence is shown in Table 2. The build-up of carbon monoxide within each room was monitored by means of graphical displays of the concentration-height profiles measured at the sample stand location on a video display unit which formed part of the data logging/analysis system.

All samples withdrawn during the course of an experiment for analysis were analysed by instruments located inside an instrument kiosk situated to the rear of the Test House and dried prior to analysis using dedicated Perma Pure drying columns. These columns exchanged water vapour through capillary tubes with walls made from semi-permeable material with a dry stream of air circulating around them. Such a technique ensured there was no adsorption of combustion products onto the surface of any solid drying agents which would have rendered the resulting gas concentration measurements inaccurate.

Each of the probes used to measure the concentration of carbon monoxide, carbon dioxide and oxygen was sampled for a 45 second period to ensure the line had been purged completely and the analyser, a Siemens Ultramat 22 + O₂ or Siemens Ultramat 23 + O₂ provided an accurate measurement of concentration at the moment a data point was logged.

Table 1. Height of sample probes

<u>On Sample Stands</u>							
Sample probe	1	2	3	4	5	6	7
Height above floor - metres	2.25	1.85	1.50	1.20	0.85	0.45	0.05
Height above floor - metres	2.25	1.80	1.40	0.95	0.50	0.05	-
<u>In Combustion Air Supply</u>							
Appliance	Combi Boiler		Central Heating Boiler		Gas Fire		
Height above floor – metres	1.7		1.3		0.1		
<u>In Draught Diverter</u>							
Appliance	Combi Boiler		Central Heating Boiler		Gas Fire		
Height above floor – metres	2.3		1.7		0.6		
<u>In Flue</u>							
Appliance	Combi Boiler		Central Heating Boiler		Gas Fire		
Height above floor – metres	4.0		4.0		4.0		

Table 2. Sample probe sequences

Heater combustion air and combustion product streams			
Sequence	Combustion air supply	⇒ Draught diverter	⇒ Flue
<i>using a Siemens Ultramat 22 + O₂ with ranges of: 0 – 500ppm CO, 0 – 10% CO₂, 0 – 25% O₂ Time taken - 2¼ minutes</i>			
In centre of release room			
Sequence	1	⇒ 2	⇒ 3 ⇒ 4 ⇒ 5 ⇒ 6 ⇒ 7
<i>using a Siemens Ultramat 22 + O₂ with ranges of: 0 – 10000ppm CO, 0 – 10% CO₂, 0 - 25% O₂ Time taken - 5¼ minutes</i>			
Other positions downstairs : Stands in remaining rooms downstairs			
Room 2	1	⇒ 2 ⇒ 3 ⇒ 4 ⇒ 5 ⇒ 6	⇒ Extract duct
Room 1 or 3 (not release room)	Extract duct	← 6 ← 5 ← 4 ← 3 ← 2 ← 1	←
Room 4	1	⇒ 2 ⇒ 3 ⇒ 4 ⇒ 5 ⇒ 6	⇒ Extract duct
Other positions downstairs : Additional stand at side of release room			
Room 2	1	⇒ 2 ⇒ 5 ⇒ 6	⇒ Extract duct
Room 1 or 3 (not release room)	6	← 5 ← Extract duct ← 2 ← 1	←
Room 4	1	⇒ 2 ⇒ 5 ⇒ 6	⇒ Extract duct
Room 3 or 1 (release room)	Extract duct	← 6 ← 5 ← 4 ← 3 ← 2 ← 1	←
<i>using a Siemens Ultramat 23 + O₂ with ranges of: 0 – 5000ppm CO, 0 – 10% CO₂, 0 - 25% O₂ Time taken for either sequence - 15¾ minutes</i>			

2.5.2 Temperatures

Temperatures were measured at 3 heights (near the ceiling, mid height, and close to the floor) on either:-

- the central stand in Room 1 and the central stand in Room 3, or
- the central stand in Room 3 and the side stand in Room 3
(The second configuration was only used in tests in which the gas appliance was positioned in Room 3.)

The temperatures were measured using LM35 semiconductor sensors.

In addition, temperatures were measured in or close to the draught diverter, and in the flue. Because of the higher temperatures, type K thermocouples were used.

2.5.3 Pressures

Furness Controls micromanometers, type FCS300, were used to measure the differential pressures between:-

- a) Outside and the room
- b) The room and the flue
- c) The pressure due to flow through the flue.
- d) The pressure due to flow through the extraction system

2.5.4 Ambient weather conditions

The prevailing weather conditions were monitored during each experiment using instrumentation local to the test enclosure. Air temperature and relative humidity were measured using a Vaisala HMD70Y, and the atmospheric pressure using a PTB100A barometer. The wind speed was monitored together with the wind direction using a Gill Instruments Ultrasonic Anemometer. The sensing elements for this instrument were positioned at a height of 9 metres and attached to a supporting mast mounted centrally on the north wall of the Test House.

2.5.5 Recording of data

The logging system was controlled by a PC in the control room, and used InstruNet modules (manufactured by GW Instruments inc.) located much closer to the instruments to record the data. In this way the noise on the signals was kept as low as possible.

The InstruNet modules were also used to control the stream selection boxes for the gas sample probes with data points recorded every 45 seconds. The data was transferred straight into an Excel spreadsheet so that real time displays could be obtained of, for example, gas concentration profiles, temperatures, weather conditions, etc. during the test. In addition the spreadsheet itself could be examined while the test was still in progress.

3 EXPERIMENTAL PROGRAMME

The experimental programme consisted of 21 tests. Details are shown in Table 3.

Three different types of gas appliance, as described in Section 2.2, and two types of air extraction, as described in Section 2.4, were used. These were located as shown in Figure 3 and Table 3. A ventilator was provided to comply with the minimum ventilation requirements of BS5440^{#1}. The positions of the ventilators are shown in Figure 3, and further details are given in Table 3. Additional ventilation was provided by leaving a 6mm gap underneath one of the doors to the volume containing the gas appliance and extract fan in most tests, as shown in Table 3.

Some tests were performed with the gas appliance and the extract fan in the same room, whilst in others the gas appliance and extract fan were in different rooms. In two of the tests the door between the room containing the gas appliance and the room containing the extract fan was closed, although gas flow between the two rooms was possible through gaps between the door and the frame.

Figure 5 shows the sequence followed in performing a test. The majority of tests had the extract fan turned on before the gas appliance was lit (a “cold” flue). In a few tests the gas appliance was lit and the flue allowed to reach steady state conditions before the extract fan was turned on (a “warm” flue). The “warm” flue condition is indicated in Table 3

Table 3. Experimental programme

Test number	Appliance Type	In room	Ventilation	Extract in room	Area of vent (cm ²)	6mm gap under door §	Comment
1	Combi Boiler	1	High level in adjacent wall	1	128	N	
2	Combi Boiler	1	Low level vent in same wall	1	128	N	
3	Combi Boiler	1	Vent adjacent to Extract	1	128	N	
4	Combi Boiler	1	Low Level Vent in Adjacent Wall	1	128	A	
5	Gas Fire	1	-	3	-	N	Cooker hood extract in Room 3
6	Central Heating Boiler	1	High level in adjacent wall	1	38	N	
7	Gas Fire	1	-	1	-	N	
8	Combi Boiler	1	High level in adjacent wall	1	128	N	Doors A and B also open
9	Combi Boiler	1	High level in adjacent wall	1	128	N	High Flow Rate
10	Combi Boiler	1	High level in adjacent wall	1	128	A	Warm flue
11	Central Heating Boiler	3	High level in adjacent wall	3	38	C	Door B not sealed
12	Central Heating Boiler	3	High level in adjacent wall	3	38	C	Door B not sealed , High Flow Rate
13	Combi Boiler	1	High level	2	128	B	
14	Combi Boiler	1	High level	2	128	B	Door A closed but not sealed
15	Combi Boiler	1	High level	3	128	C	
16	Combi Boiler	1	High level	3	128	C	High Flow Rate
17	Central Heating Boiler	1	High level	3	38	C	
18	Central Heating Boiler	1	High level	1	38	A	Warm flue
19	Central Heating Boiler	1	High level	2	38	B	Door A closed but not sealed, "Warm" flue
20	Central Heating Boiler	1	High level	2	38	B	Warm flue
21	Gas Fire	1	-	2	-	N	"Warm" flue

Notes: § N = No gap, A = Door A, etc.

4 EXPERIMENTAL PROCEDURE

When the experiment involved a cold flue, the extract fan was run at a high rate and the gas appliance lit. The flow in the flue was monitored by the differential pressure due to flow and also by the temperatures in the flue and the draught diverter. The level of extract was reduced until the flue started to pull in order that the flow rate required to just reverse the flue could be determined. The appliance was then extinguished and the extract rate increased. The flue was allowed to cool before the gas appliance was re-lit. This time the flow rate in the extract was only reduced to a level where flow reversal in the flue could be maintained in spite of variations in ambient conditions, such as gusts of wind. (This demanded care - too low a flow rate resulted in the flue spontaneously pulling normally, and too high a rate would distort the experimental results. In practice, the flow rate used was increased from a low level until spontaneous flue pulling was not observed.)

When the experiment involved the use of a “warm” flue, the extract fan was started at a high rate and the gas appliance lit. The extract rate was reduced until the flue started to pull so that the flow rate required to just reverse the flue could be determined. The extract fan was then turned off, and the flow of combustion products through the flue caused it to heat up. When both the temperature and the flow in the flue had stabilised, the extract fan was re-started and the flow increased until normal flow in the flue was replaced by air from outside flowing down the flue. This flow rate was maintained for the rest of the test.

The phase of the test where reversed flow was maintained was continued until one of the following was reached:-

- a) a steady-state concentration of carbon monoxide had been measured within the room containing the appliance; or
- b) ½ hour had elapsed (using the Combi boiler); or
- c) 1 hour had elapsed (using the Central Heating boiler); or
- d) 3 hours had elapsed (using the Gas Fire).

The final phase of the experiment determined the extra ventilator area required to cause the flow in the flue to revert to normal. The extraction rate was maintained while the ventilator(s) were gradually opened. “Normal” flow in the flue was deemed to have been produced when the temperatures and differential pressures in the flue were similar to those observed when the appliance was operating normally.

5 RESULTS

The Appendix to this report contains details of the measurements made during each of the 21 tests conducted. Each test has associated data which includes:

- a) Details of the room configuration, average wind speed/direction and general test conditions in Table 4.
- b) The prevailing weather conditions (wind speed/direction, temperature, humidity, pressure).
- c) The variation in carbon monoxide, carbon dioxide and oxygen concentrations with time in the combustion air supply, at the draught diverter, and in flue to the appliance.
- d) The variation in carbon monoxide, carbon dioxide and oxygen concentrations with time in the rooms of the house. This information is presented as concentration-height profiles.
- e) The variation in carbon monoxide, carbon dioxide and oxygen concentrations with time in the extraction system.
- f) Flow through the extraction system.
- g) Extra ventilator area needed to make the flue revert to normal operation.
- h) Temperatures inside the house.

The results obtained are discussed in detail below.

5.1 COMBI BOILER

The Combi boiler was located in Room 1, the largest on the ground floor of the house, because of its relatively high power rating. It was found that an extract rate of 60 – 180m³/hr was sufficient to maintain flue reversal for a short period. The large spread of values was probably due to the different configurations used in the tests. Thus when Door A was closed an extract rate of 60 - 120m³/hr was needed, but when the ventilator and extract fan were in different rooms an extract rate of 140 - 180m³/hr was needed. The extra, or excess, extraction was probably required because of greater adventitious ventilation openings (e.g. cracks around windows, in walls and floors) present in the larger volumes. The rate of extraction determined above was not sufficient to maintain flue reversal during the steady state phase of the test. This may have been due to small pressure perturbations in the flue caused by to external wind conditions, or variations in the “drive” of combustion products at the base of the flue. Thus for the steady state phase, rates of 160 - 190m³/hr were required in tests involving Room 1 only, rising to 250m³/hr where the extract fan was operating in a different room.

This “excess” flow rate in the extraction system is defined as:

$$\text{flow rate used} - \text{flow rate required to just reverse the cold flue}$$

The extraction rates measured in each test are shown in Table 4.

Carbon monoxide and carbon dioxide spilled into the room as soon as the flue was reversed. The concentration of each increased rapidly, and steady state conditions were obtained in the release room after only a few minutes. An example of the concentration profiles (for carbon monoxide, carbon dioxide and oxygen respectively) in the release room (for Test 1) is shown in Figures 6, 7 and 8. The build up of combustion products in the other rooms was slower, and was affected by the configuration of the boiler, extract fan, and open doors in the house. A summary of the concentrations of carbon monoxide, carbon dioxide and oxygen measured is shown in Table 5.

Table 4. Test Conditions

Test Number	Appliance	Extraction rate required to just reverse flue (m ³ /hr)	Average extraction rate used in test (m ³ /hr)	Extra ventilator area needed to get flue to pull (cm ²)	Atmospheric pressure (mbar)	Outside temperature (Celsius)	Relative humidity (%)	Wind speed (m/s)	Wind direction (degrees relative to magnetic North)
1	Combi Boiler	120	184	121	980	13.3	59	4.3 ± 1.6	215 ± 19
2	Combi Boiler	110	190	<140	979	6.9	76	2.2 ± 1	265 ± 41
3	Combi Boiler	90	166	170	998	10.9	93	5.2 ± 0.9	46 ± 10
4	Combi Boiler	60	180	120	985	14.1	97	4.8 ± 1.2	81 ± 11
5	Gas Fire	100	159	100	1005	15.9	50	2.6 ± 1.4	267 ± 53
6	Central Heating Boiler	60	79	85	986	19	58	2.1 ± 1.1	214 ± 84
7	Gas Fire	40	63	64	987	15.1	987	3.1 ± 1.4	219 ± 37
8	Combi Boiler	120	180	121	982	13.9	982	3.2 ± 1.6	213 ± 39
9	Combi Boiler	-	349 ‡	>120	976	9	976	3.5 ± 1.5	147 ± 24
10	Combi Boiler	60	316 †	460 + 50m ³ /hr flow reduction	983	13.2	101	3.2 ± 0.9	52 ± 17
11	Central Heating Boiler	85	118	74	987	15.9	64	2.5 ± 1.2	212 ± 44
12	Central Heating Boiler	85	245 ‡	330	987	17.7	60	2.4 ± 1.2	196 ± 41
13	Combi Boiler	140	223	225	1001	19.3	62	1.1 ± 0.8	159 ± 59
14	Combi Boiler	170	237	70	999	20.7	52	1.2 ± 0.7	94 ± 53
15	Combi Boiler	180	240	Unable to maintain reversal	992	18.5	66	3.4 ± 0.9	63 ± 21
16	Combi Boiler	180	336 ‡	270	992	17.8	68	3.3 ± 1	56 ± 15
17	Central Heating Boiler	95	170	80	997	14.2	70	6.4 ± 1.6	72 ± 17
18	Central Heating Boiler	40	219 †	240	984	15.9	81	1.3 ± 0.8	190 ± 69
19	Central Heating Boiler	60	312 †	310	982	15.5	85	1.3 ± 0.9	173 ± 72
20	Central Heating Boiler	70	267 †	310	982	15.3	63	3 ± 1.7	231 ± 40
21	Gas Fire	60	314 †	370	1007	16.5	60	1.7 ± 0.8	300 ± 44

Notes: ‡ High extraction rate

† "Warm" flue

Table 5. Gas Concentrations

Test Number	Time to Oxygen concentration in release room <18%	Time to Oxygen concentration in feed <18%	Carbon Monoxide concentration in release room after 1 cycle (ppm)	Maximum Carbon Monoxide concentration in release room (ppm)	Maximum Carbon Monoxide concentration in extract (ppm)	Maximum amount of Carbon Monoxide produced (m ³ /hr)	Maximum Carbon Dioxide concentration in release room (% v/v)	Maximum amount of Carbon Dioxide produced (m ³ /hr)	Minimum Oxygen concentration in release room (% v/v)
1	<6 minutes	min value 20.0%	660	1300 @ 27 min.	1098	0.202	2.27	3.5	16.87
2	<6 minutes	min value 20.6%	455	455 @ 6 min	355	0.067	2.26	3.72	17.17
3	<6 minutes	min value 20.2%	600	1020 @ 27 min	940	0.156	2.41	3.63	16.89
4	<6 minutes	min value 20.5%	1020	1085 @ 17 min	991	0.178	2.38	3.81	16.86
5	min value 20.2%	min value 20.4%	< 7	-	6	0.001	0.48	0.67	20.11
6	27 minutes	min value 20.2%	20	< 32	37	0.003	1.79	1.37	17.81
7	min value 19.3%	min value 20.0%	< 36	-	43	0.003	0.94	0.56	19.33
8	<6 minutes	min value 19.8%	615	745 @ 32 min	587	0.106	2.12	3.1	17.23
9	min value 18.5%	min value 20.1%	785	1160 @ 27 min	979	0.341	1.38	3.98	18.48
10	min value 18.3%	min value 20.4%	~1100	1110 @ 64 min	912	0.288	1.49	3.79	18.3
11	min value 18.6%	min value 20.7%	< 22	-	17	0.002	1.47	1.58	18.59
12	min value 19.6%	min value 20.2%	350	350 @ 6 min	349	0.085	0.83	1.56	19.63
13	<6 minutes	min value 20.3%	900	1050 @ 17 min	739	0.164	2.18	3.57	17.07
14	<6 minutes	min value 16.1%	2440	> 10500 @ 22 min	4539	1.075	3	2.48	14.15
15	<6 minutes	-	1320	1320 @ 6 min	650	0.156	2.07	2.94	17.3
16	<6 minutes	min value 19.8%	1215	1215 @ 6 min	623	0.21	1.9	3.77	17.45
17	min value 20.2%	min value 20.2%	< 30	-	19	0.003	1.39	1.51	18.54
18	min value 19.3%	min value 20.3%	280	425 @ 59 min	365	0.08	0.94	1.65	19.33
19	min value 18.3%	min value 18.9%	415	2390 @ 90 min	763	0.238	0.94	1.44	19.18
20	min value 19.3%	min value 20.2%	305	590 @ 74 min	397	0.106	0.93	1.51	19.34
21	min value 20.5%	min value 20.7%	< 20	-	4	0.001	0.29	0.73	20.49

The spillage of the combustion products also raised the temperature in the room. The rise in temperature measured during each test is shown in Table 6.

It is defined as:-

$$\text{temperature at end of steady state period} - \text{temperature at start of test}$$

Table 6. Temperatures.

Test number	Temperature rise during test (Celsius)					
	Room 1 (centre)			Room 3 (centre)		
	top	middle	bottom	top	middle	bottom
1	21.2	10.3	2.1	0.8	0.3	0.1
2	23.0	6.2	2.0	-0.1	0.2	0.2
3	24.9	10.2	2.0	0.7	0.0	0.6
4	22.3	7.9	1.9	-0.4	0.1	0.1
5	23.4	20.5	10.7	13.3	12.9	8.6
6	15.2	7.0	1.7	0.6	0.5	0.3
7	32.9	30.7	18.0	1.2	2.7	2.2
8	21.0	4.6	2.1	3.9	2.3	0.7
9	17.3	10.2	1.1	0.9	-0.3	-0.3
10	18.3	9.1	2.1	-0.2	0.3	-0.3
11 ^{†‡}	20.2 [†]	6.7 [†]	1.9 [†]	18.5 [‡]	3.5 [‡]	2.3 [‡]
12 ^{†‡}	11.7 [†]	6.3 [†]	1.1 [†]	9.8 [‡]	2.0 [‡]	1.0 [‡]
13	22.2	10.6	1.9	0.3	0.7	-0.6
14	20.6	12.9	3.4	-0.3	-0.3	0.8
15	14.1	5.0	1.0	2.9	1.4	0.1
16	20.0	10.0	2.2	6.6	4.8	1.5
17	11.1	4.2	2.2	3.7	3.2	1.3
18	11.4	6.3	1.2	0.3	0.1	0.5
19	11.5	8.5	2.9	0.7	0.0	-0.1
20	12.3	7.1	2.9	2.1	1.2	-0.1
21	23.4	20.6	9.1	3.2	3.6	3.0

Notes: † Temperatures measured at Room 3 (centre)
‡ Temperatures measured at Room 3 (side)

In the final part of the test the external ventilator area was increased until the flue started to pull normally. The results obtained are given in Table 4.

5.2 CENTRAL HEATING BOILER

The power rating of the Central Heating boiler was considerably less than the Combi boiler (15.4kW c.f. 35.4kW). Consequently this boiler was used in Room 3 as well as Room 1 to compare the effect of operating the appliance in different room volumes as well as different appliances operating in the same volume. The tests on different ventilator location were not repeated.

It proved to be much easier to reverse the flue using this appliance, compared with the Combi boiler, as demonstrated shown by the values of extraction rate shown in Table 4.

Carbon monoxide and carbon dioxide spilled into the room as soon as the flue was reversed. The time to reach steady state concentrations of combustion products was quickest in the smallest room volume when using the highest extract rate. Steady state conditions were normally reached within 30 minutes of starting to reverse the flue. A summary of the concentrations of carbon monoxide, carbon dioxide and oxygen measured during each test is shown in Table 5. The amount of carbon monoxide produced by this boiler was significantly less than that produced by the Combi Boiler. However, higher extraction rates did produce more than tests using low extraction rates.

The spilling of the combustion products also raised the temperature in the room. The rise in temperature measured during each test (see Section 5.1) is given in Table 6.

The Central Heating boiler required less “excess” extraction (see Section 5.1) to maintain a reversed flue than the Combi boiler. Consequently less extra ventilator area was required to cause the flue to revert to normal flow than was found with the Combi boiler. (This result does not apply to tests using extraction rates which were larger than those required to just maintain a reversed flue, such as tests where the boiler was started before the extraction system, or a higher extraction rate was set as part of the experimental conditions.)

5.3 GAS FIRE

In all three tests the Gas Fire was located in Room 1. The extraction rate needed to reverse the flue tended to be similar to that required by the Central Heating boiler, as shown by the values of extraction rate shown in Table 4.

Carbon monoxide and carbon dioxide spilled into the room as soon as the flue was reversed. The low power rating of the appliance (6.45 kW) resulted in a slow build up of combustion products. However, the initial period where the concentrations of carbon monoxide and carbon dioxide altered significantly was less than 1½ hours in all tests. A summary of the concentrations of carbon monoxide, carbon dioxide and oxygen measured is shown in Table 5. The amount of carbon monoxide produced by the Gas Fire was significantly less than produced by the Combi Boiler.

The spilling of the combustion products also raised the temperature in the room. The rise in temperature measured during each test (see Section 5.1) is given in Table 6.

The three tests carried out using the gas fire used very different configurations. Thus no reliable figure for the extra ventilator area required to cause the flue to revert to normal flow could be determined.

6 DISCUSSION

6.1 COMBUSTION PRODUCTS

When the flow in the flue was reversed, all the combustion products entered the room containing the appliance. Thus the concentrations of carbon monoxide and carbon dioxide in the volume around the boiler will increase until the rate at which they are being produced is equal to the rate at which they are being removed. This is known as “steady state” conditions. The net effect of convection, ventilation and extraction in the room produces the profile recorded during each test.

Figures 9, 10, and 11 show the maximum concentration of carbon monoxide and carbon dioxide in the release room plotted against extraction rate for the three gas appliances used. The concentration of carbon dioxide generally falls as the extraction rate is increased, while the concentration of carbon monoxide appears to rise at higher flow rates. In most cases the volume containing the appliance and the extraction fan (release room only, or with gas appliance and extract fan in different rooms) does not appear to affect the maximum concentration of carbon dioxide in the release room. (The exceptions are those tests with the gas appliance in Room 1, the extraction fan in Room 2 and the intervening door closed, which will be discussed later.) The effect of extract flow rate on the production of combustion products cannot be seen clearly in these plots. However, by assuming that all the combustion products are taken into the extraction system, a value for the quantities produced by the gas appliance can be calculated by the equation:

$$\begin{array}{l} \text{Rate of combustion} \\ \text{product production} \end{array} = \frac{\text{Concentration of combustion product in extract system}}{\text{Flow rate in extraction system}} \times$$

Figures 12, 13, and 14 show the rate of carbon monoxide and carbon dioxide production plotted against extraction rate. The effect of the flow rate can now be seen much more clearly. The rate of carbon dioxide production by the appliance, based on its power rating, is also shown on the graph. The experimental measurements are close to this line. The amount of carbon monoxide produced does appear to increase as the flow rate is increased in both the Combi and Central Heating boilers. The concentration of carbon monoxide produced by the gas fire (<40 ppm) was too low to be accurately resolved by the analyser (range 0 – 10000 ppm).

6.1.1 Low extract rates

A Low Extract Rate is enough to maintain flow reversal in the flue. As shown in Table 4, these were found to be 160 - 190m³/hr for the Combi boiler, 80 - 170m³/hr for the Central Heating boiler, and 60 - 160m³/hr for the Gas Fire.

Previous work^{#2} showed that the Combi Boiler spilled significant amounts of carbon monoxide when the flue was partially blocked, even if the air supply to the boiler was not vitiated. This was attributed to the design of the draught diverter allowing combustion products to re-circulate within the boiler case when the flue was restricted or blocked. A schematic diagram of this flow is shown in Figure 15. Thus when the flow in the flue is reversed by an extraction fan, the air supplied to the burner is a combination of air from the room and combustion products from the draught diverter.

Hence, a higher concentration of carbon monoxide will be produced than expected from the vitiation of the room air and, because the flow in the flue is reversed, this will enter the room. The Central Heating boiler and the gas fire produced only small quantities of carbon monoxide at the low extract rates. These concentrations were too low to be accurately resolved by the analyser (range 0 – 10000 ppm).

The values measured are presented on Figures 9 – 14 and in Table 5.

6.1.2 High extract rates

A high extract rate was used either to represent extraction equipment operated near to typical domestic extraction maximum rates, or to reverse a warm flue. (A warm flue required a much higher extract rate to cause flow reversal initially than a cold flue.) Again the concentrations of carbon monoxide and carbon dioxide measured are shown on Figures 9 – 14 and in Table 5. The quantity of carbon monoxide produced increased slightly for the Combi boiler, but much more dramatically for the Central Heating boiler. The higher levels measured may have been due to the higher extraction rate causing flame distortion. The difference in response between the two boilers may have been due, for example, to the design of the draught diverters and burners.

6.1.3 Closed door between Gas Appliance and Extract

In three tests the door between the room containing the gas appliance and the room containing the extraction apparatus was kept closed. The carbon monoxide concentrations measured in the release room and the quantities of carbon monoxide produced were very considerably elevated with the Combi boiler, significantly elevated with the Central Heating boiler, and not noticeably changed with the gas fire, compared with similar tests where the door was kept open. The values measured are shown on Figures 9 – 14 and in Table 5.

Figure 16 shows the maximum values of carbon dioxide and minimum values of oxygen concentration measured in the air supply to the burner of the appliance. For most tests the oxygen concentration was greater than 19³/₄%. The two exceptions are Tests 14 (with the Combi boiler) and Test 19 (with the Central Heating boiler) which both had the door between the gas appliance and extract closed. The concentration of carbon dioxide in the release room was also significantly different in these two tests. Thus the closure of the door appears to have a significant effect. Tests 13 and 18 were similar tests to 14 and 19, but with the intervening door open. Figures 17 and 18 show the distribution of the carbon dioxide as a function of height in the release room, just before the end of the steady state period of the test. In the tests where the door was open, the concentration of carbon dioxide was almost uniform below the height of the boiler, but increased rapidly above. A much more uniform increase was observed between floor level and ceiling when the door was closed. At all positions the concentration of carbon dioxide measured was at least ½% greater in the tests where the door was closed, with the greatest difference being seen at the height of the air inlet to the gas appliance.

The general increase in concentration indicated that less air was being extracted from the release room when the door was closed (and preferentially more from the other room). The difference in profile showed that the flow pattern in the room was different. Consequently the air supply to the burner had less oxygen and more carbon dioxide when the door was closed than when it was open. Thus the boilers produced more carbon monoxide than would be expected with the extraction rates used.

The gas fire had a much lower power rating than either boiler. The position of the gas fire (near the floor) produced a much more uniform profile of gas concentration within the room (as shown on Figure 19), diluting the combustion products in a significantly larger volume. This combination of factors may explain the observation that there was no significant difference between the tests where the door was closed and open.

6.2 TEMPERATURES

6.2.1 Temperature Rise

Temperatures were measured at 3 heights on either:-

- a) the central stand in Room 1 and the central stand in Room 3, or
- b) the central stand in Room 3 and the side stand in Room 3,

as described in section 2.5.2. The heat given off by the appliances in normal operation raised the temperature in the room. Values for this rise were obtained during tests utilising a “warm” flue, and are shown in Table 7. The temperature rise recorded during the flue reversal phase of the test in the centre of the release room is shown on Figures 20 - 22. Although significant temperature rises were seen close to the ceiling, a person sitting in the room would only experience changes in temperature at the two lower measurement heights. The rise in temperature at these positions would probably not be enough to cause alarm to an occupant with either boiler. The largest temperature rise was seen with the gas fire. Although the occupant might turn the fire down, they are unlikely to be aware of the flue products entering the room.

Table 7. Temperature rise when appliance operated normally

Test	Temperature rise - Celsius		
	Ceiling	Mid	Floor
10, Combi Boiler	8	3	1
18, Central Heating Boiler	6	2	0
19, Central Heating Boiler	5	2	1
20, Central Heating Boiler	6	2	2
21, Gas Fire §	>8	>7	>5

Notes: § Steady state conditions were not reached

6.2.2 Temperatures in the draught diverter and flue

These measurements were used to check for the direction of flow in the flue. During normal flow in the flue, the hot flue gases rapidly heated the flue. Flue reversal produced a rapid drop towards atmospheric ambient temperature. The temperature in the draught diverter was affected by the proximity of the hot gas appliance, and also dilution of the flue gases by fresh air during flue reversal. However an indication of the direction of flow in the flue could be inferred from these two measurements.

The measurements from Test 10 are shown in Figure 23.

6.3 DIFFERENTIAL PRESSURES

Differential pressures were measured as described in Section 2.5.3. and those measured in the extract system were used to determine the flow rates. The differential pressures in the flue were used to measure qualitatively the flow in the flue. The flow measurements were found to be in good agreement with the measurements described in Section 6.2.1, as shown on Figure 23.

The measurements of differential pressure between the room and the flue, and between the room and the outside are also presented in Figure 23.

6.4 EXTRA VENTILATOR AREA REQUIRED

The final stage of each test involved increasing the ventilator area into the volume containing the gas appliance and the extract until the flue started to flow normally. As the extract system pulled from the flue, the ventilators, and any other opening, increasing the ventilator area reduced the tendency for the flow in the flue to remain reversed. The reduction of flow down the flue resulted in a lower dilution of the hot combustion products by cool air, and this resulted in an increase in the temperature recorded at the draught diverter. This can be seen in Figure 23, between 74 and 93 minutes. However once the change to the normal direction of flow in the flue occurred, the differential pressure due to flow in the flue indicated that almost normal flow rates were produced almost immediately. Again this can be seen on Figure 23, at 93 minutes. The change was thus observed as a gradual reduction in flow down the flue as the ventilator area was increased, and then a sudden reversal and rapid increase in flow up the flue without any further increase in ventilator area being needed.

The first stage of a test usually involved determining the extract flow to reverse a cold flue. To maintain reversal in the flue during the experiment a higher extraction rate was needed (see Section 4). In some tests the extraction rate was deliberately set to a greater value than needed just to maintain reversal. Finally in some tests a warm flue was reversed, which required a greater extraction rate than reversing a cold flue, and this higher extraction rate was used during the test. Thus a range of extraction flow rates were used in these tests. The extra ventilator area needed depended on such things as the characteristics of the particular gas appliance, the characteristics of the flue in the prevailing weather conditions, the ventilation available (both adventitious and specifically provided) and the suction from the extraction system. The extra ventilator area found necessary to make the flue flow normally is shown in Figure 24.

If, however, the “excess” flow rate in the extraction system is plotted against extra ventilator area, as in Figure 25, the results appear to be much clearer, with the extra ventilator area needed appearing to increase linearly with excess extract rate. If the line for “All appliances” is extended to the axes, it appears that an extra ventilator area of about 40cm² would be needed for a zero excess flow rate. This extra ventilator area probably represented the effort necessary to overcome an established reversed flue flow. The excess extract rate may be impossible to estimate in most realistic situations. However, in all the tests in this programme the extra ventilator area required was more the 50cm² quoted in BS5440^{#1}, and, as can be seen in Figure 25, much larger excess ventilator area were needed in some tests.

7 CONCLUSIONS

- a) Flue reversal can be obtained with Cannon Gas Fire and Central Heating Boiler using low ($<90\text{m}^3/\text{hr}$) extraction rates. Higher extraction rates were required with the Combi boiler to produce flue reversal.
- b) The rate of production of carbon monoxide was dependent on the appliance.
- c) The Central Heating Boiler at low extraction rates produced very little carbon monoxide. Larger quantities were produced at higher ($>200\text{m}^3/\text{hr}$) extraction rates. The Combi Boiler, even at the lowest extraction rates used produced much more carbon monoxide. Increasing the extraction rate resulted in an increased production of carbon monoxide, but the effect was not as pronounced as with the Central Heating boiler.
The quantity produced by the gas fire was small during each test.
- d) Closure of an intervening door between the appliance and the extract system caused dramatic / significant increases in the quantity of carbon monoxide produced by the Combi and Central Heating Boilers respectively
This was probably due to a change in flow patterns and reduction in the rate of extract from the room containing the gas appliance.
- e) The temperature rise alone, compared to normal operation of the appliances, would be unlikely to warn an occupant of a developing toxic atmosphere.
- f) The flow in the flue exhibited considerable hysteresis between two stable flow regimes.
Initially the flue removed products from the appliance. The flow was normal. The extraction rate was increased gradually and the flow up the flue was reduced until it was zero. Suddenly flow in the flue was reversed, and rapidly increased without any further increase in the extract rate.
Similarly, at the end of the test when the ventilator area was gradually increased, the reverse flow in the flue was slowly reduced to zero, until the flow reverted to a normal direction and increased rapidly without further increase in the ventilator area.
- g) A linear relationship (with some scatter) was seen between the extra ventilator area required to make the flue revert to normal flow and the excess extraction rate.
- h) In all the tests the extra ventilator require to make a reversed flue flow normally was greater than 50cm^2

8 RECOMMENDATIONS

The experimental program in phase 2 will use the new Test House at GRTC. Consequently some tests should repeat the configurations used in Phase 1, but in a different house. The repeatability of the results in different properties can thus be examined.

Additionally, tests should examine:-

- Low level extractors (e.g. tumble driers)
- Different types of appliances (e.g. decorative flame effect gas fires)

9 BIBLIOGRAPHY

1. BS5440,Part 2 : 1989 (Specification for the installation of ventilation for gas appliances)
2. R.W. Hill and G. Pool; “Full Scale Experiments to Study the Effect of Oxygen Depletion and Ventilator Location on the Production of Carbon Monoxide from Open Flued and Flueless Gas Appliances Operating under Vitiating Conditions” – GRTC R2532 (1998)

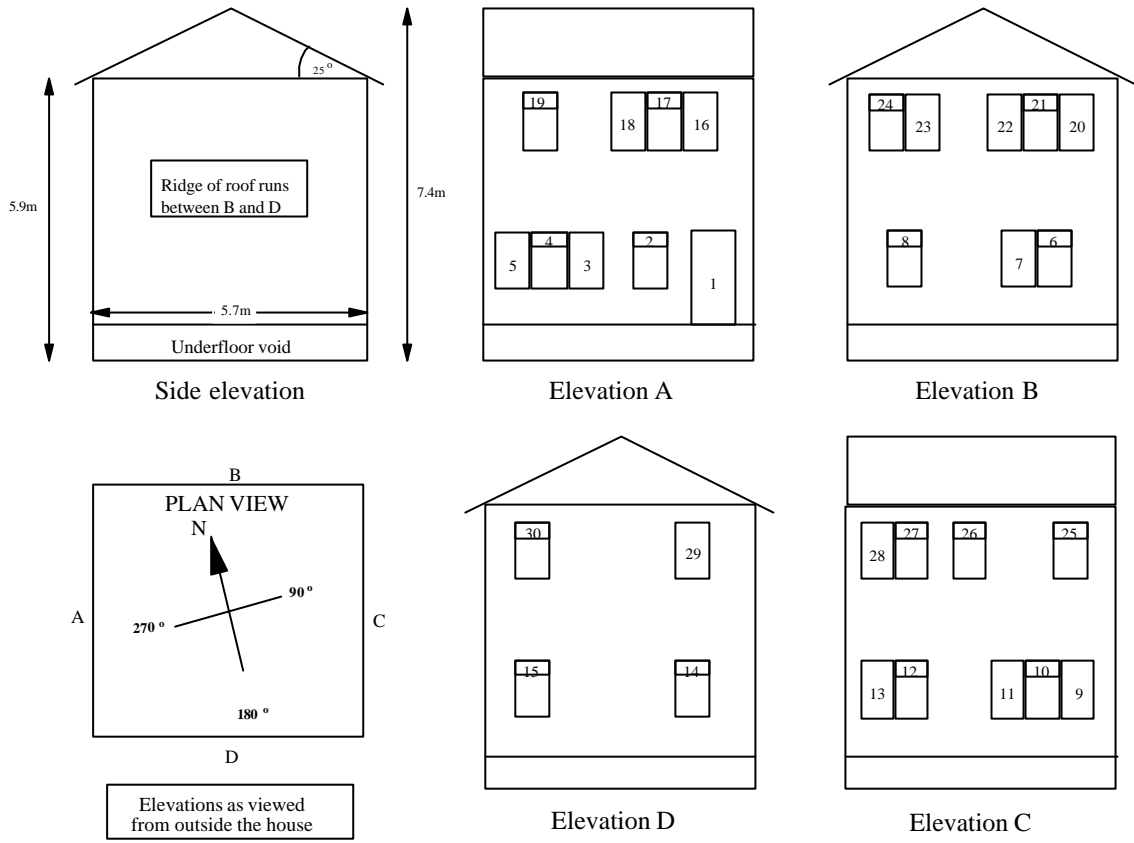
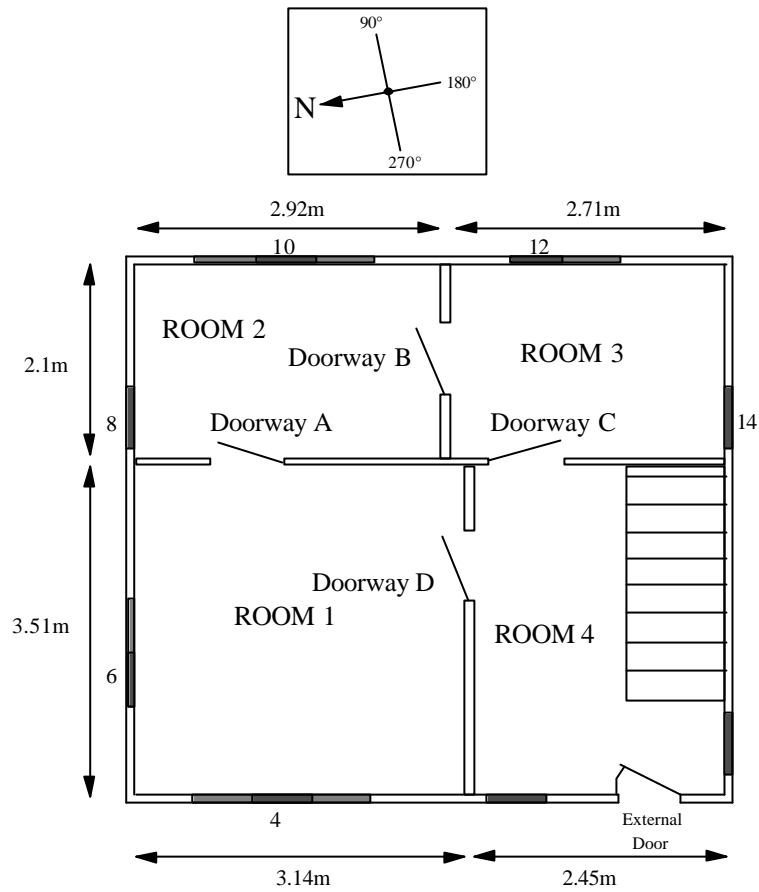
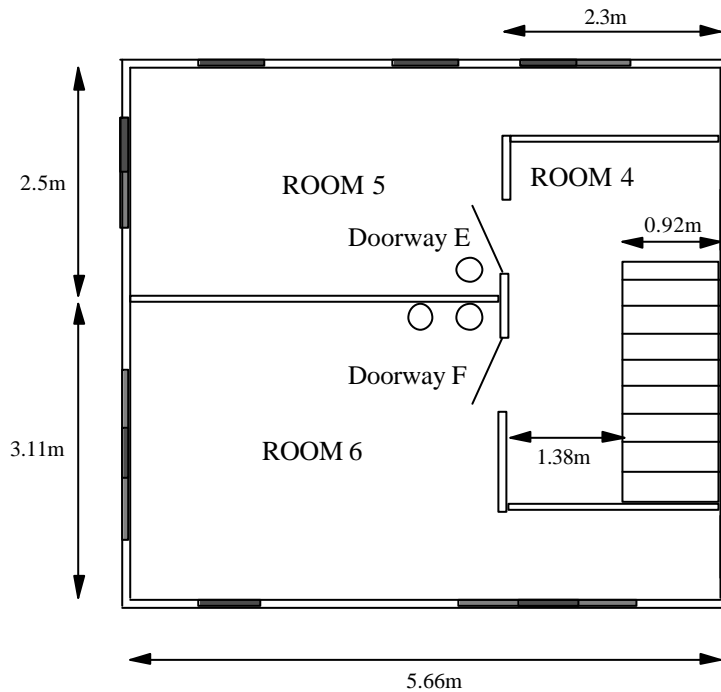


Figure 1. Elevation of house

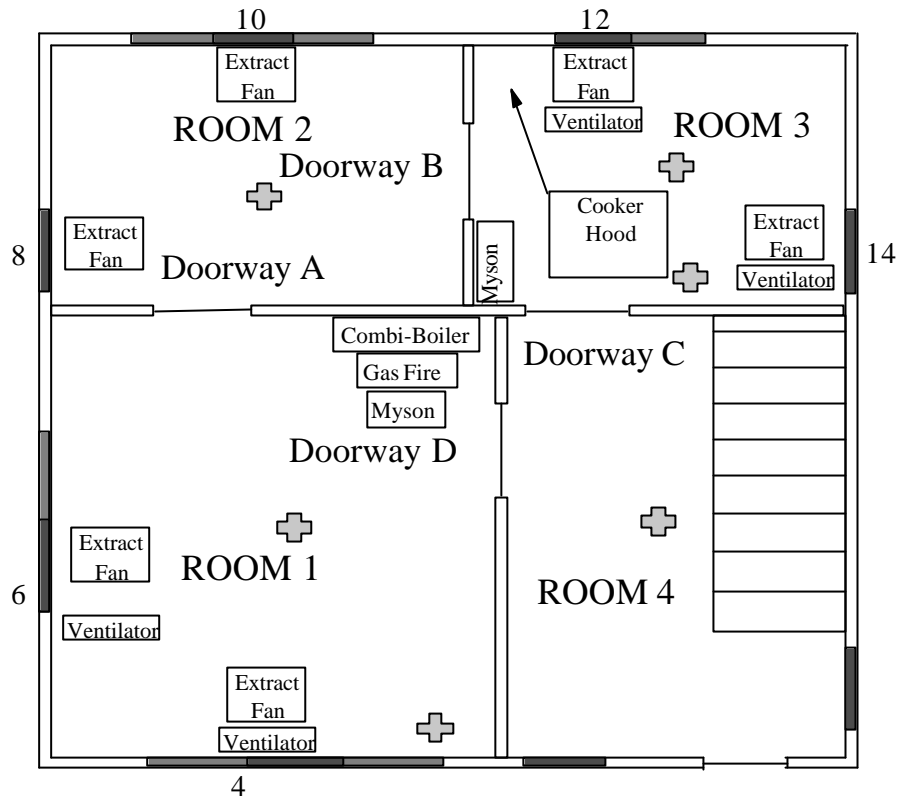


LOWER FLOOR



UPPER FLOOR

Figure 2. Room configuration in the two-storey, multi-room enclosure showing the approximate location of the room partitions, doors and windows



⊕ Location of sample stand

Figure 3. Layout of appliances, ventilators, and extraction units

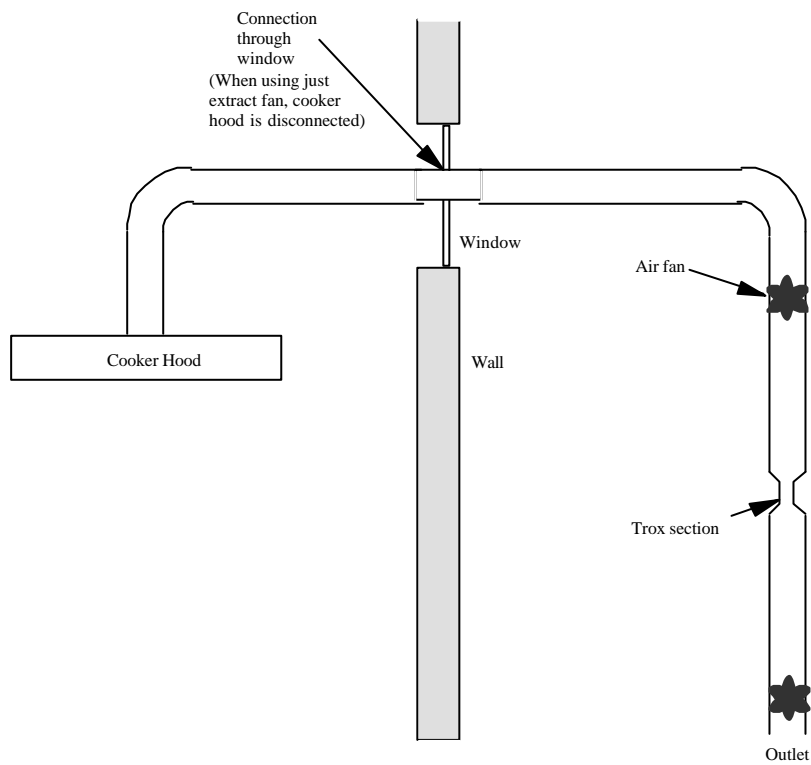


Figure 4. Schematic diagram of extraction system

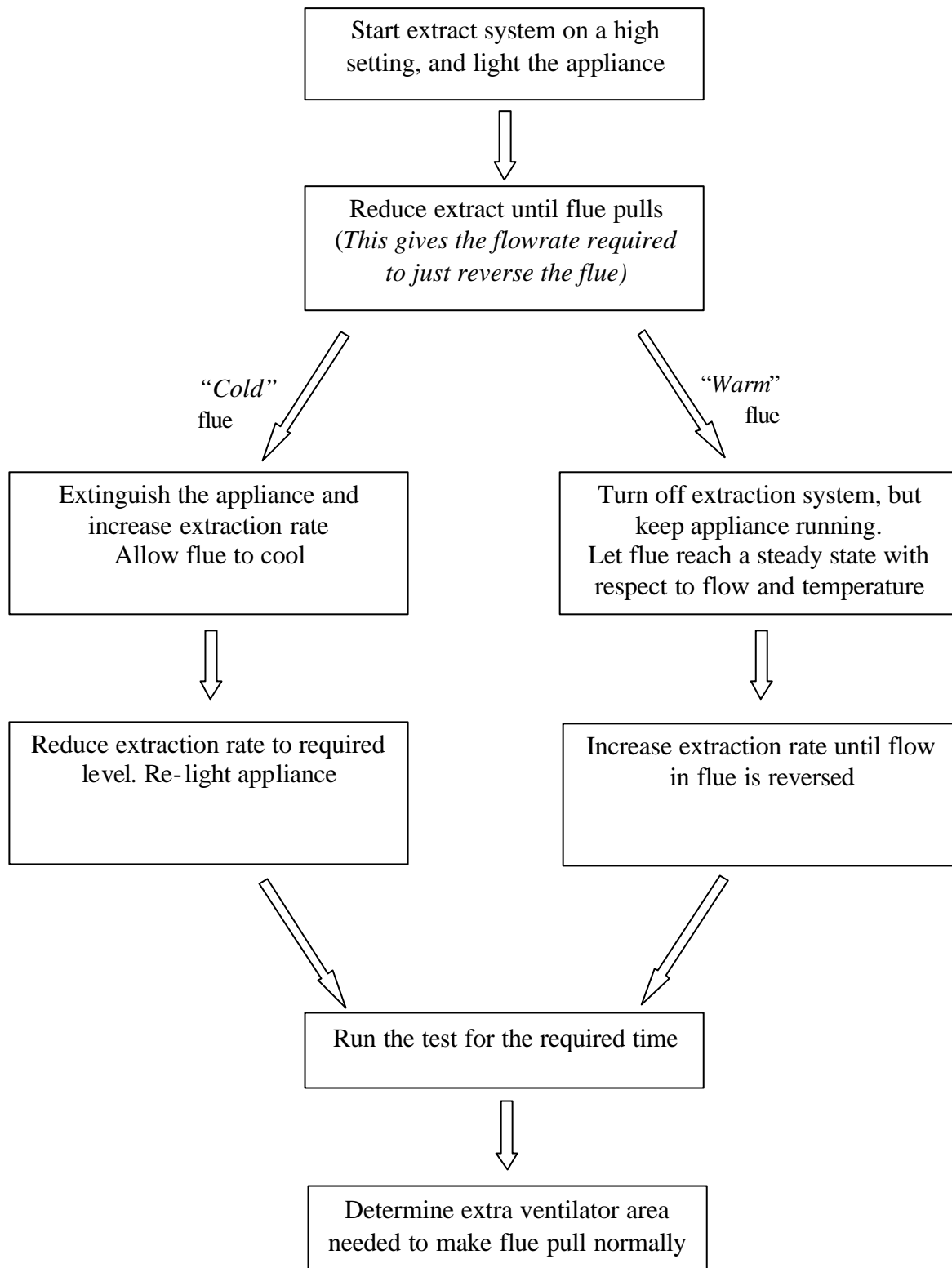


Figure 5. Sequence diagram for conducting a test

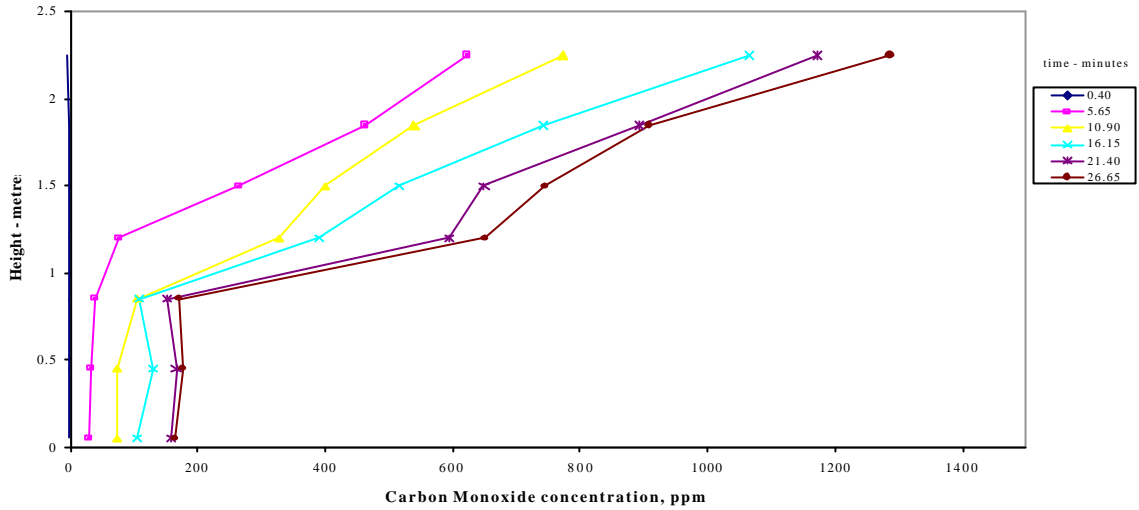


Figure 6. Test 1, Carbon Monoxide concentration in the centre of Room 1

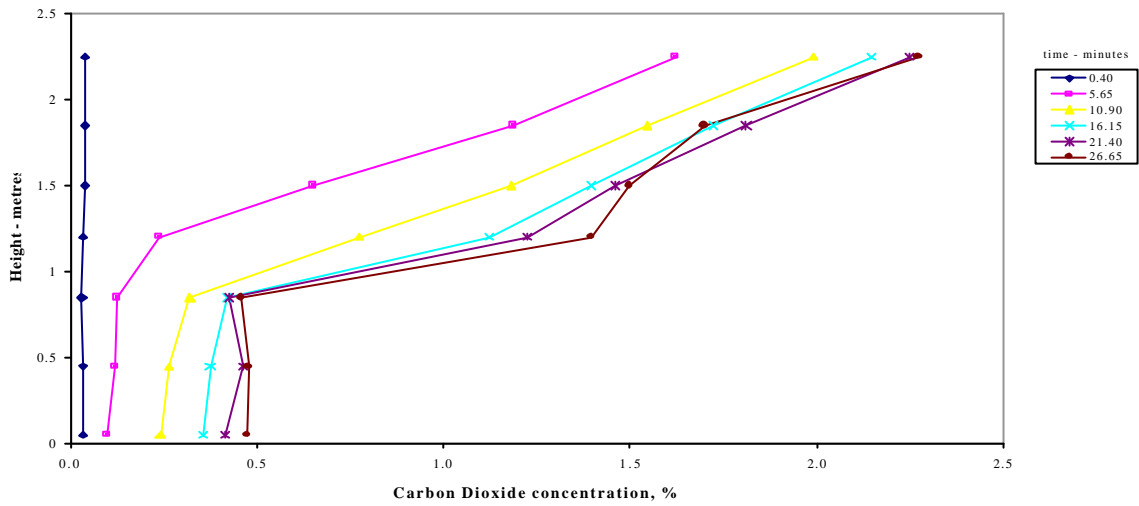


Figure 7. Test 1, Carbon Dioxide concentration in the centre of Room 1

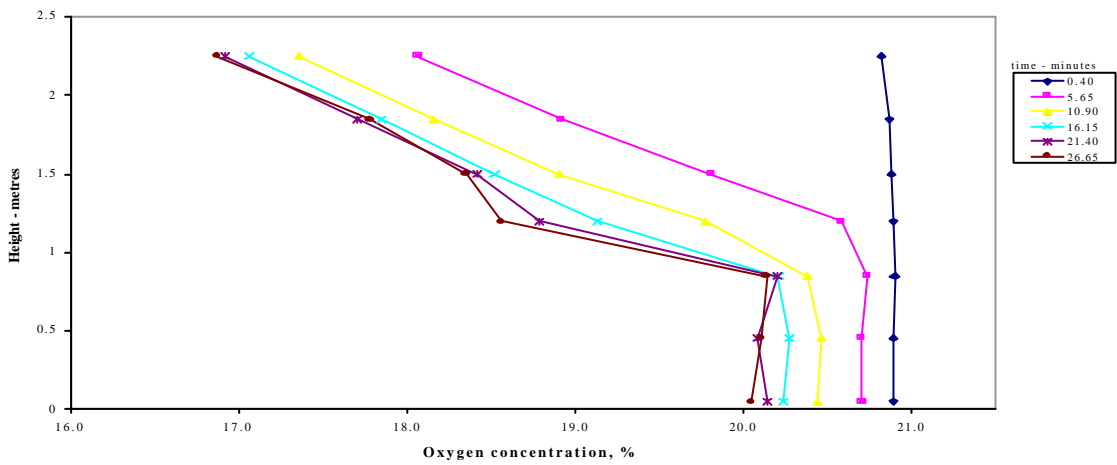


Figure 8. Test 1, Oxygen concentration in the centre of Room 1

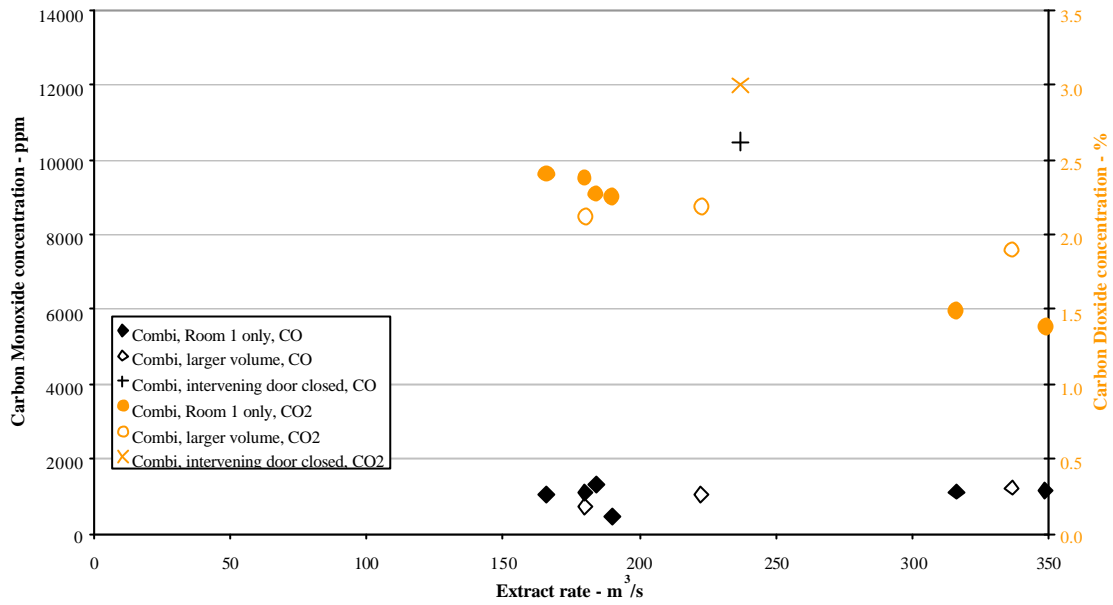


Figure 9. Maximum concentration in release room v. flowrate, Combi Boiler

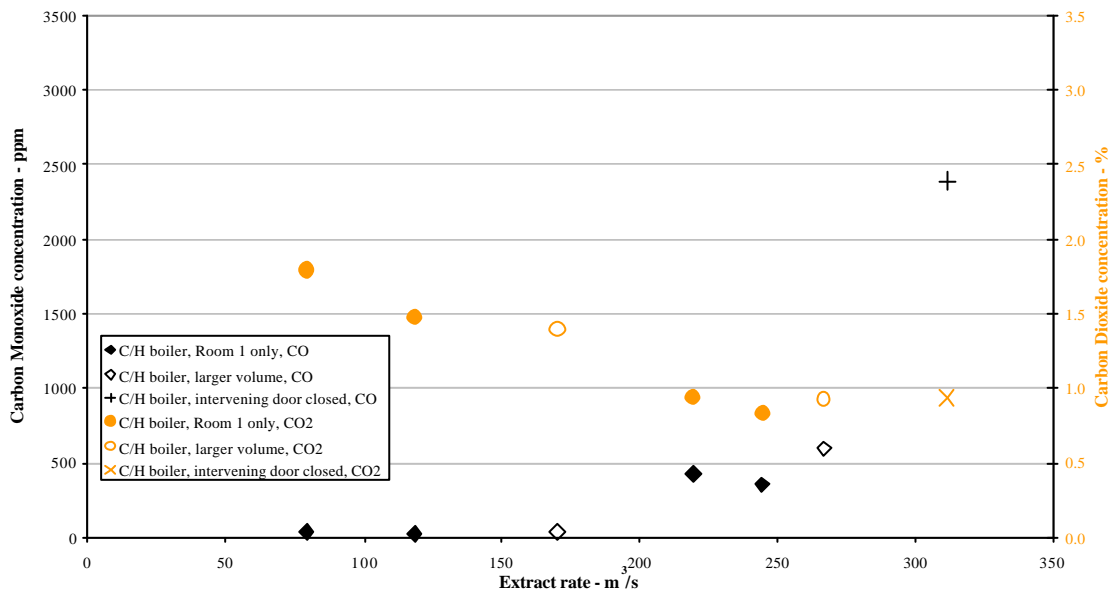


Figure 10. Maximum concentration in release room v. flowrate, Central Heating Boiler

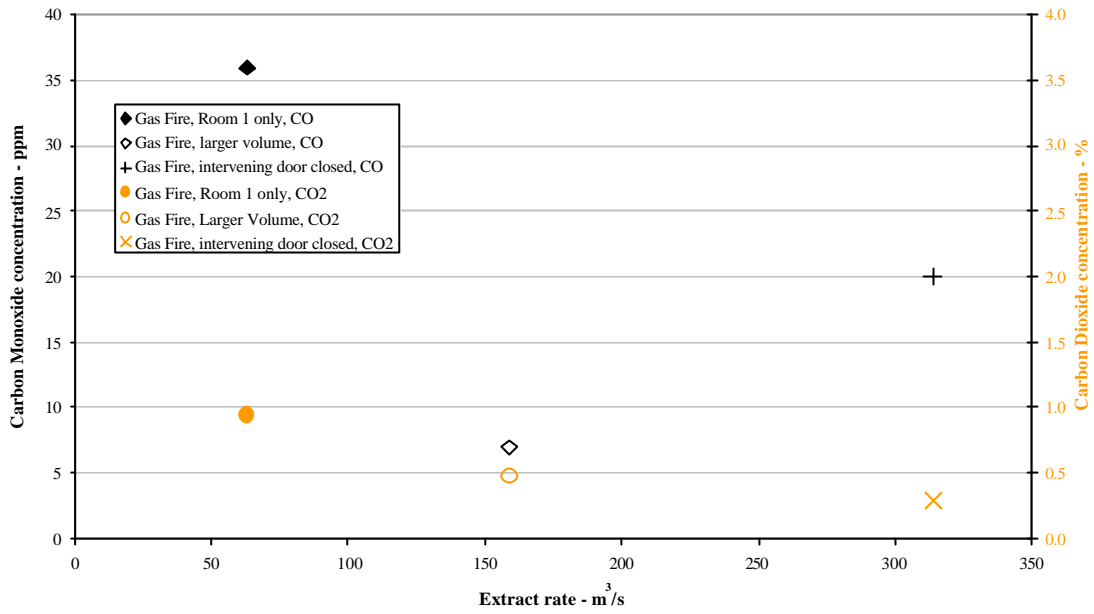


Figure 11. Maximum concentration in release room v. flowrate, Gas Fire

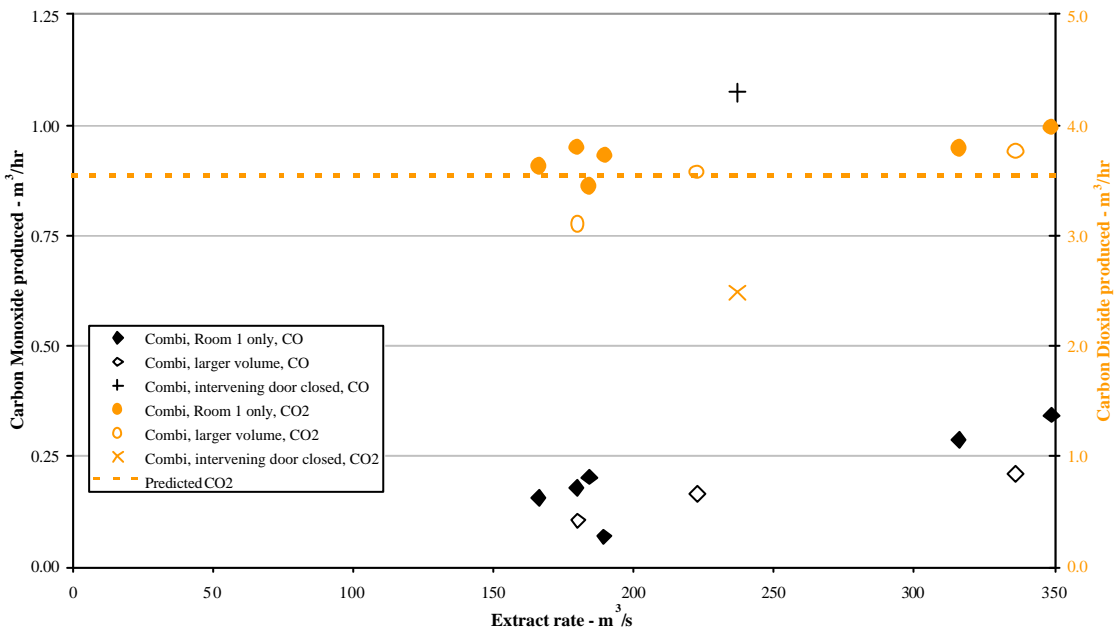


Figure 12. Quantity produced, Combi boiler

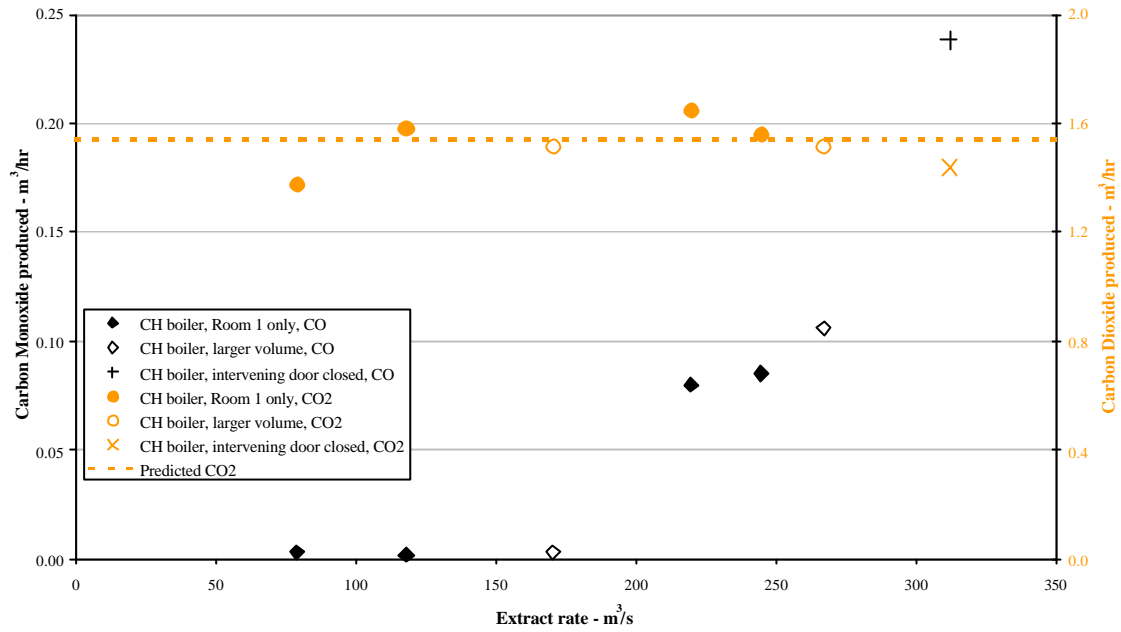


Figure 13. Quantity produced, Central Heating Boiler

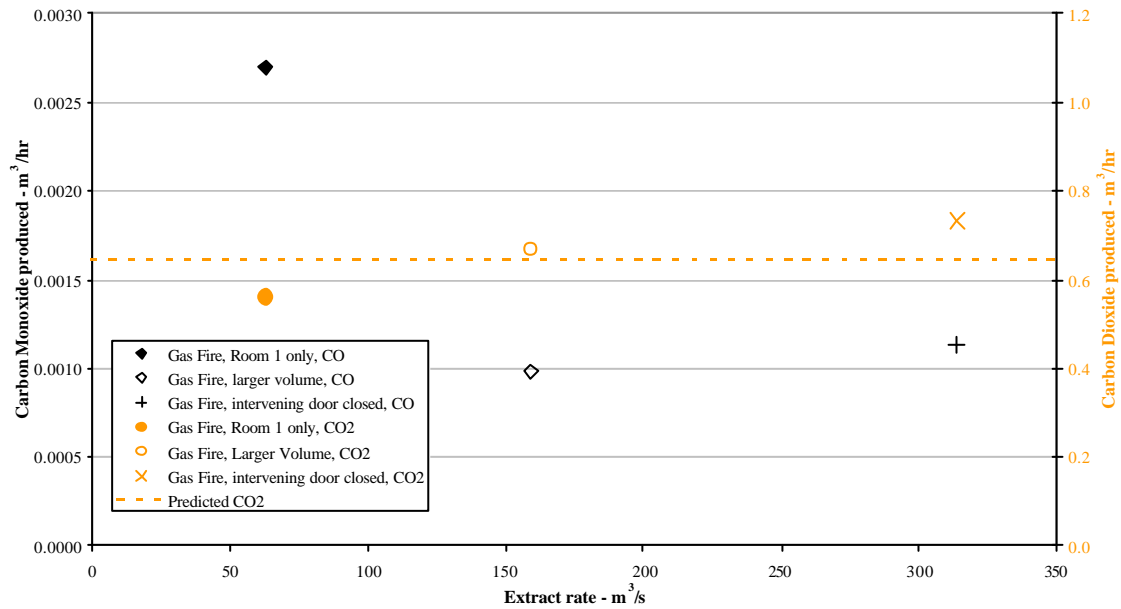


Figure 14. Quantity produced, Gas Fire

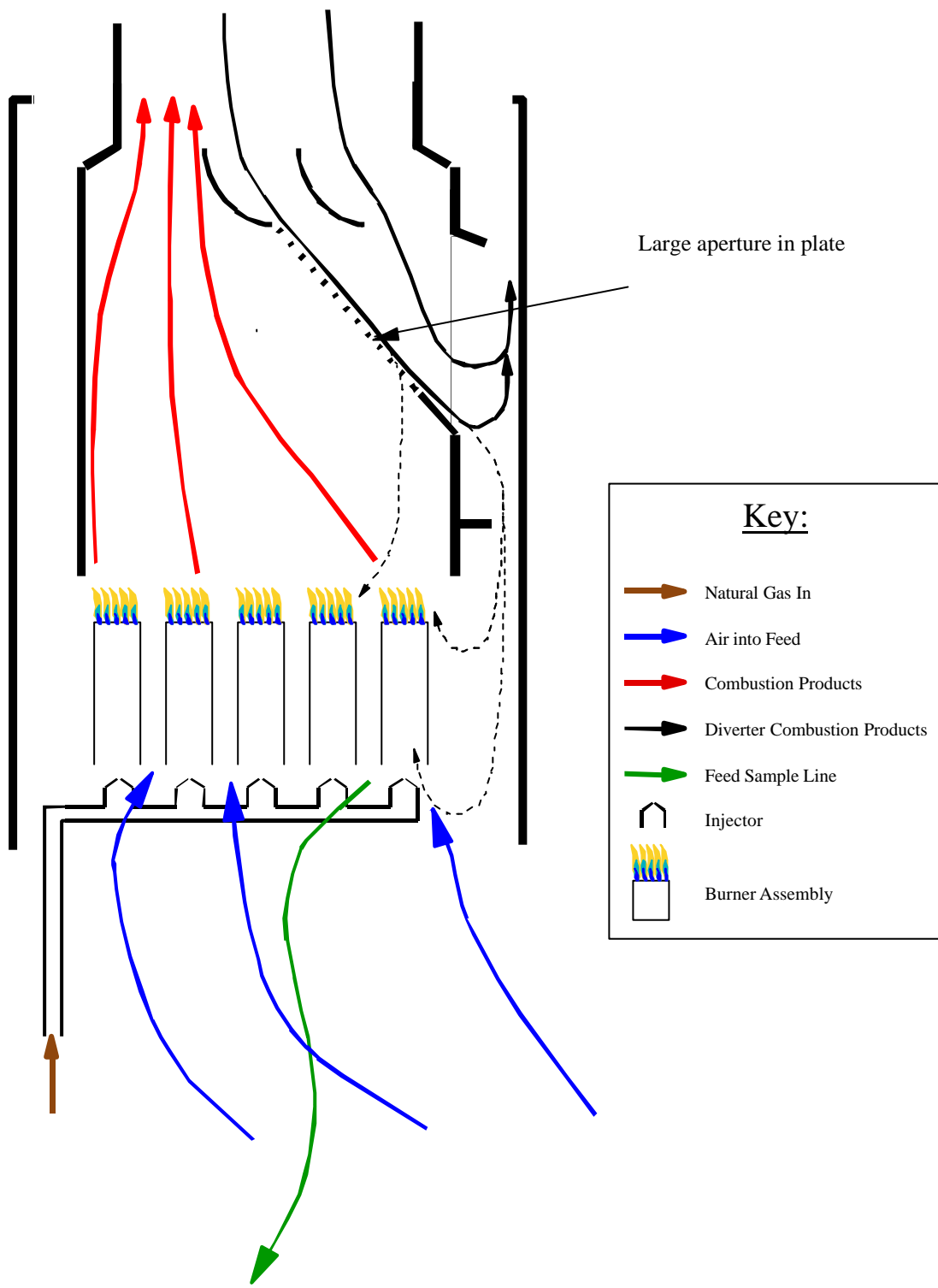


Figure 15. Possible flow in and around Combi boiler

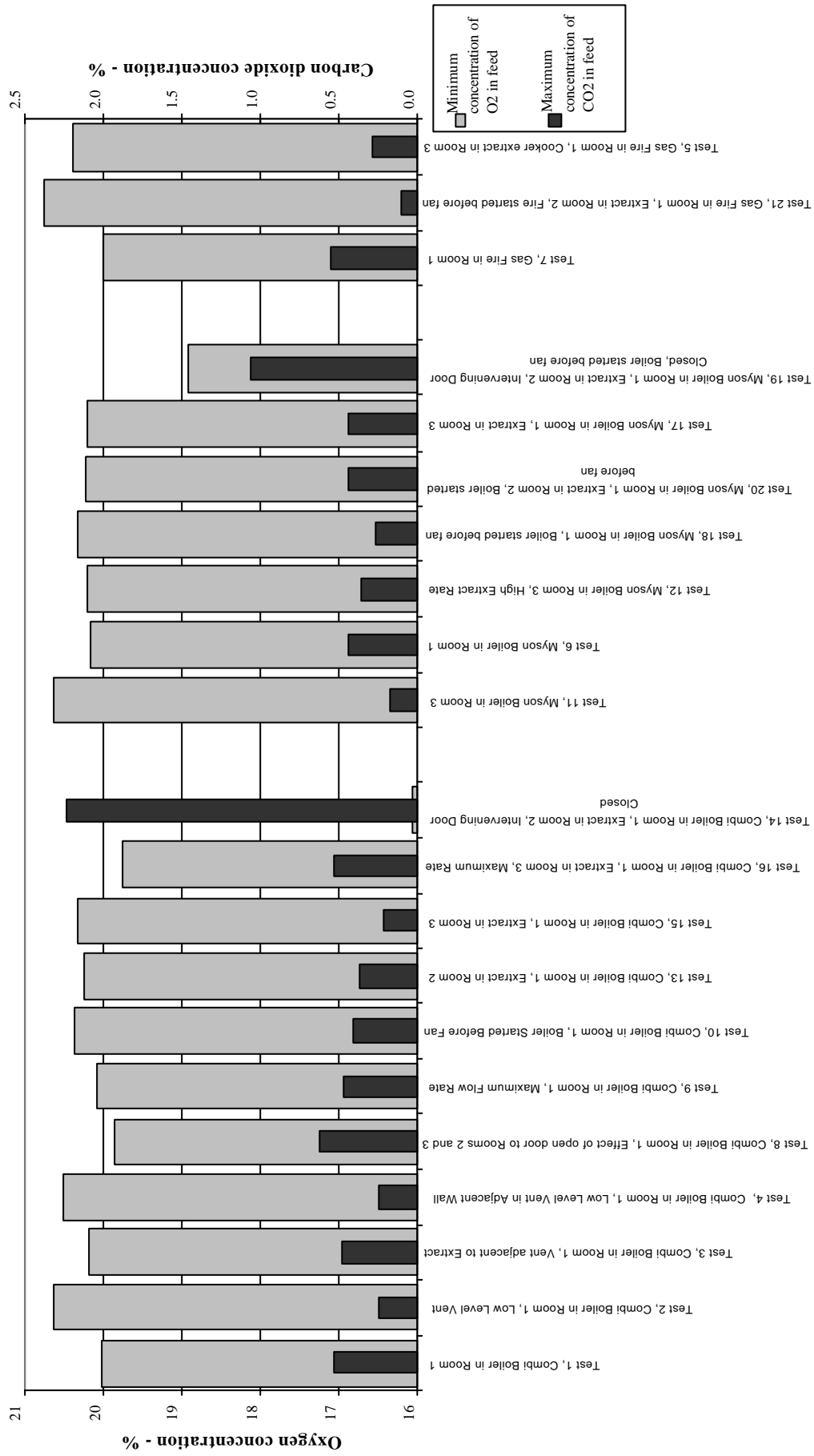


Figure 16. Concentrations of Oxygen and Carbon Dioxide in Air supply to Burner

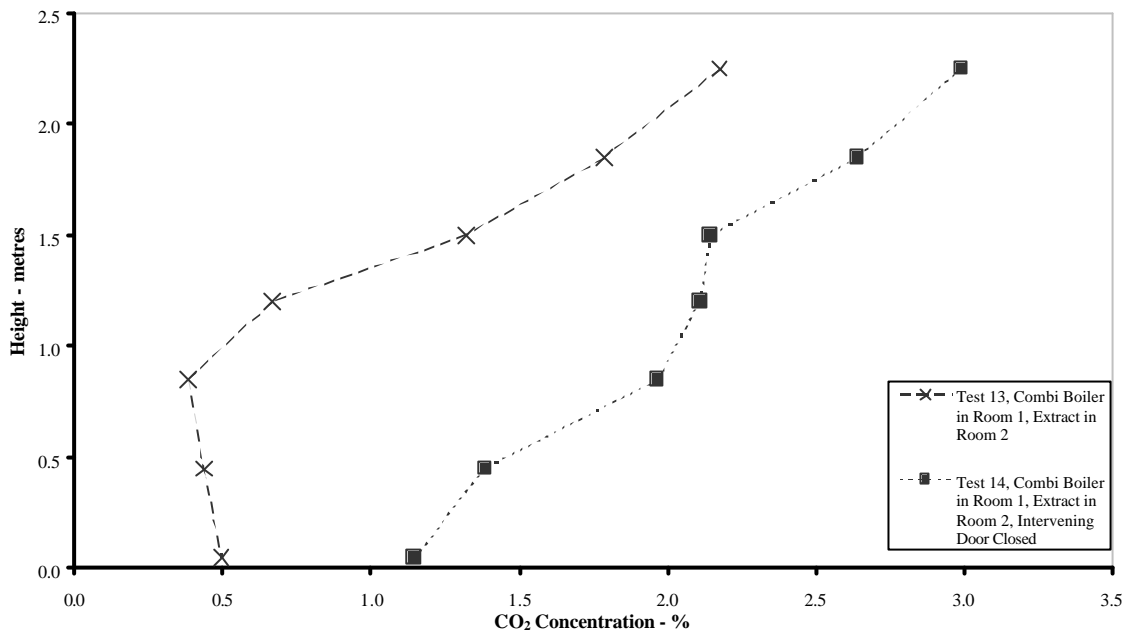


Figure 17. Concentration of carbon dioxide in release room in Tests 13 and 14

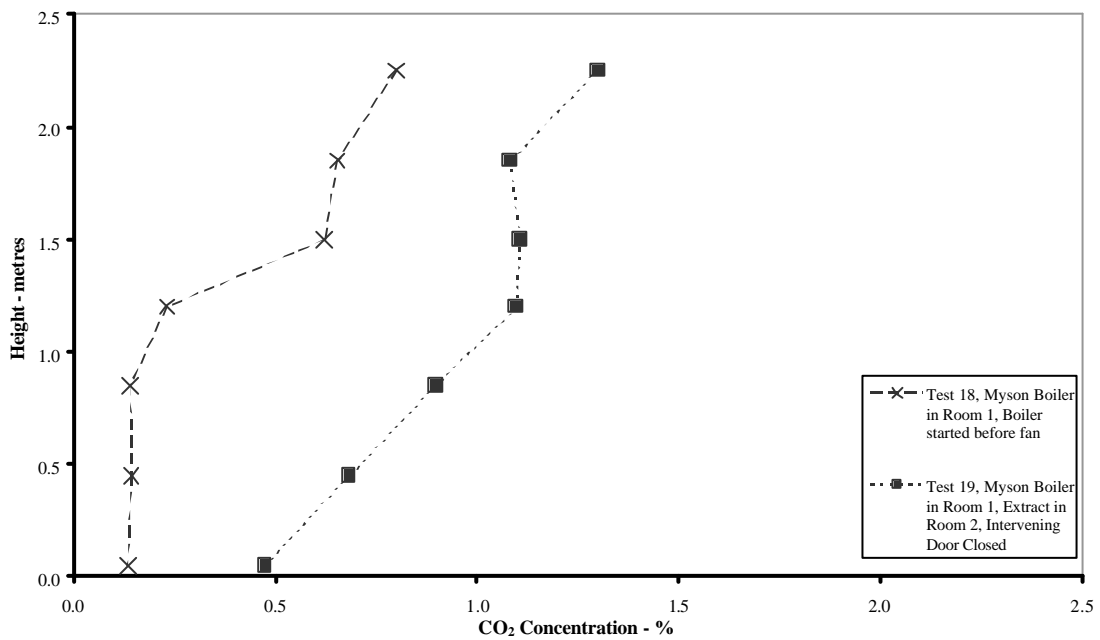


Figure 18. Concentration of carbon dioxide in release room in Tests 18 and 19

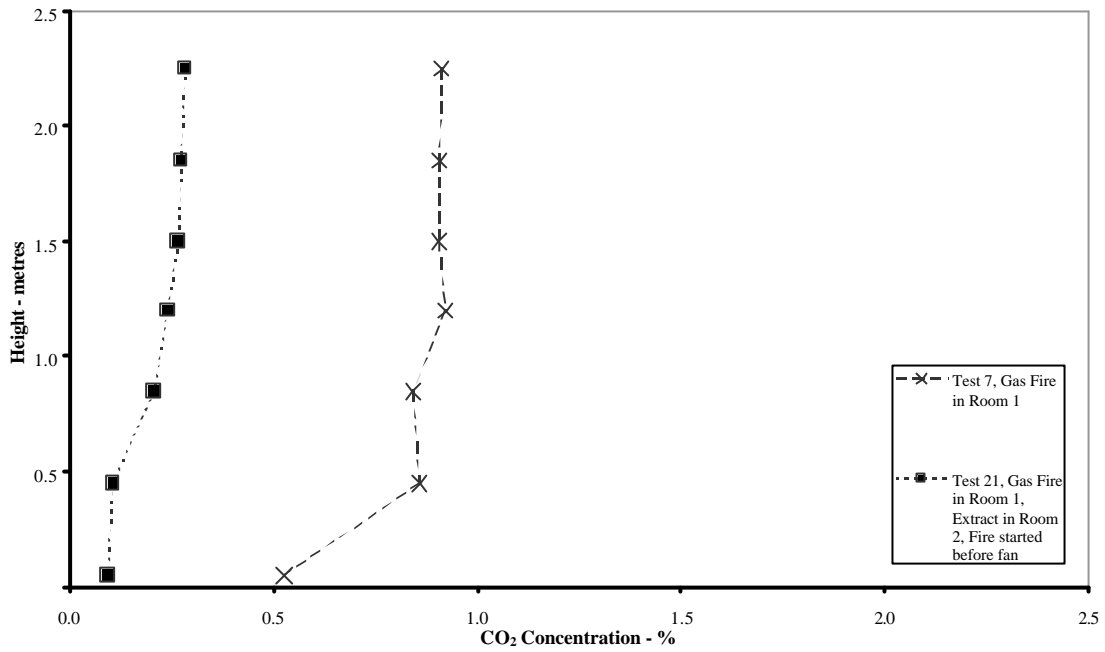


Figure 19. Concentration of carbon dioxide in release room in Tests 7 and 21

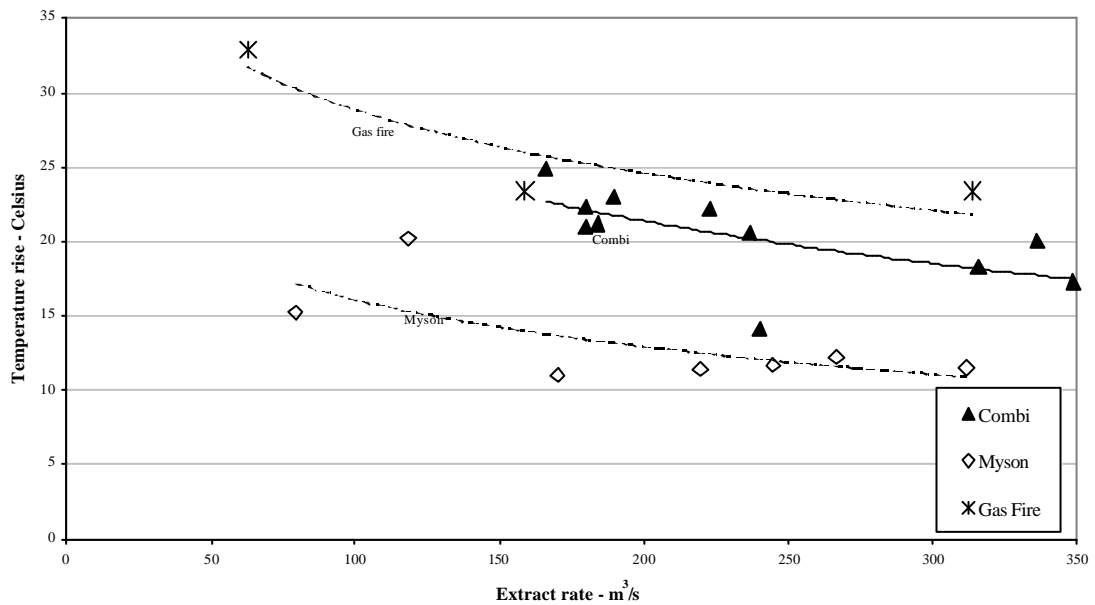


Figure 20. Temperature rise measured in release room close to the ceiling

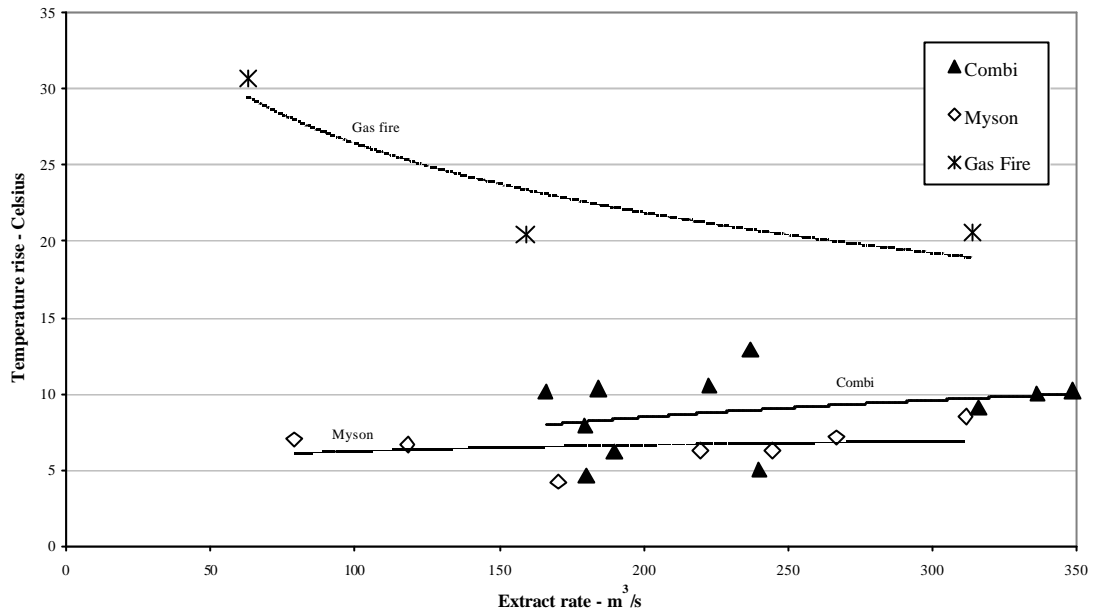


Figure 21. Temperature rise measured in release room at mid height

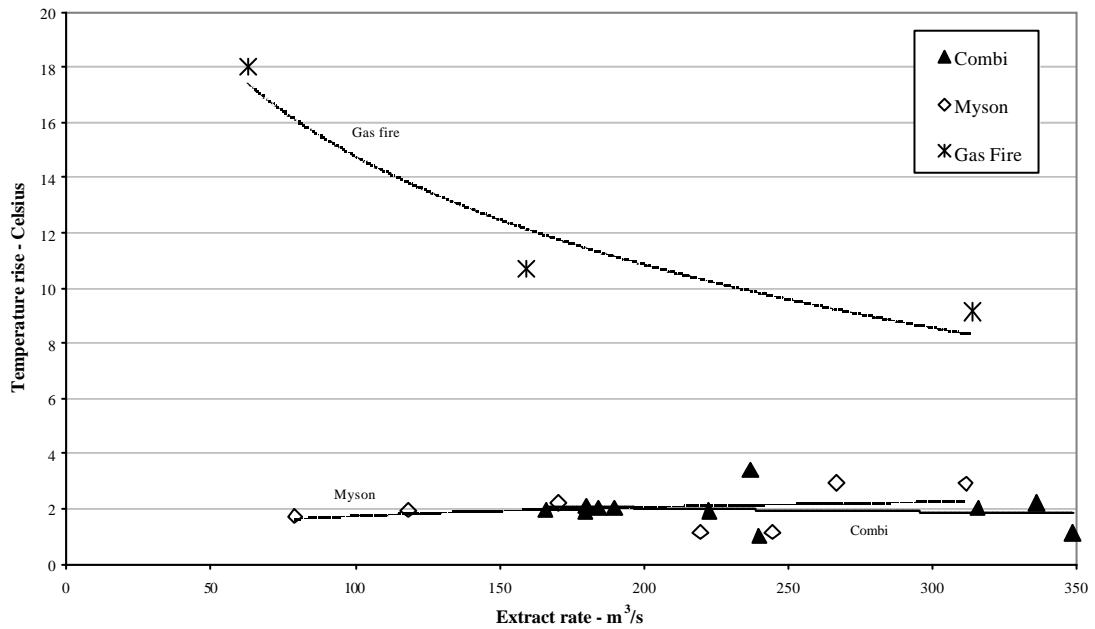


Figure 22. Temperature rise measured in release room close to the floor

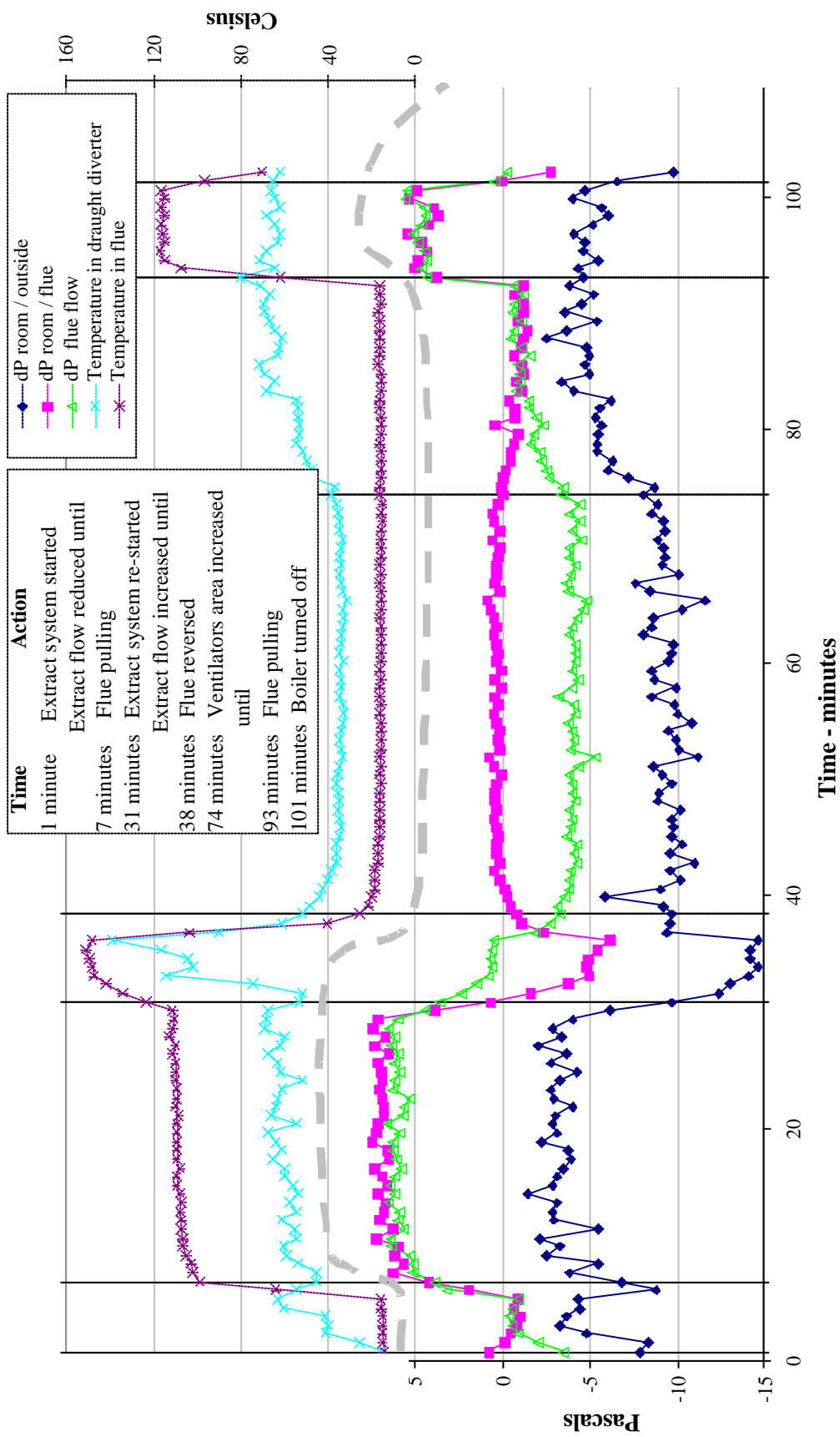


Figure 23. Differential Pressures and Flue Temperatures for Test 10

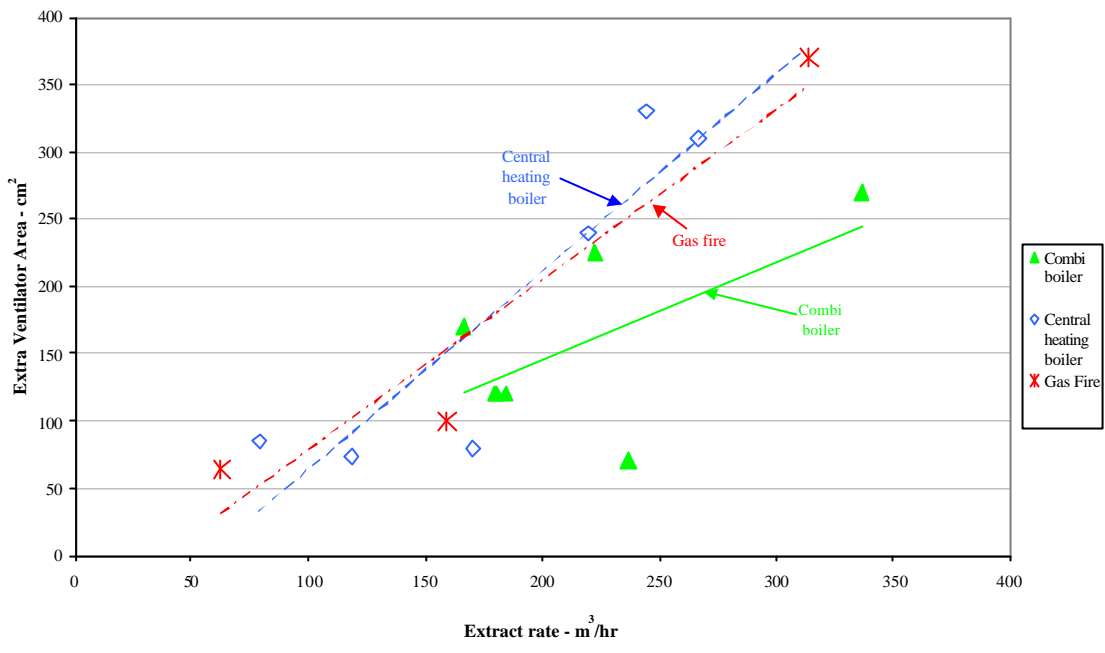


Figure 24. Extra ventilator area required to cause normal flow in the flue v. flow rate in extraction system

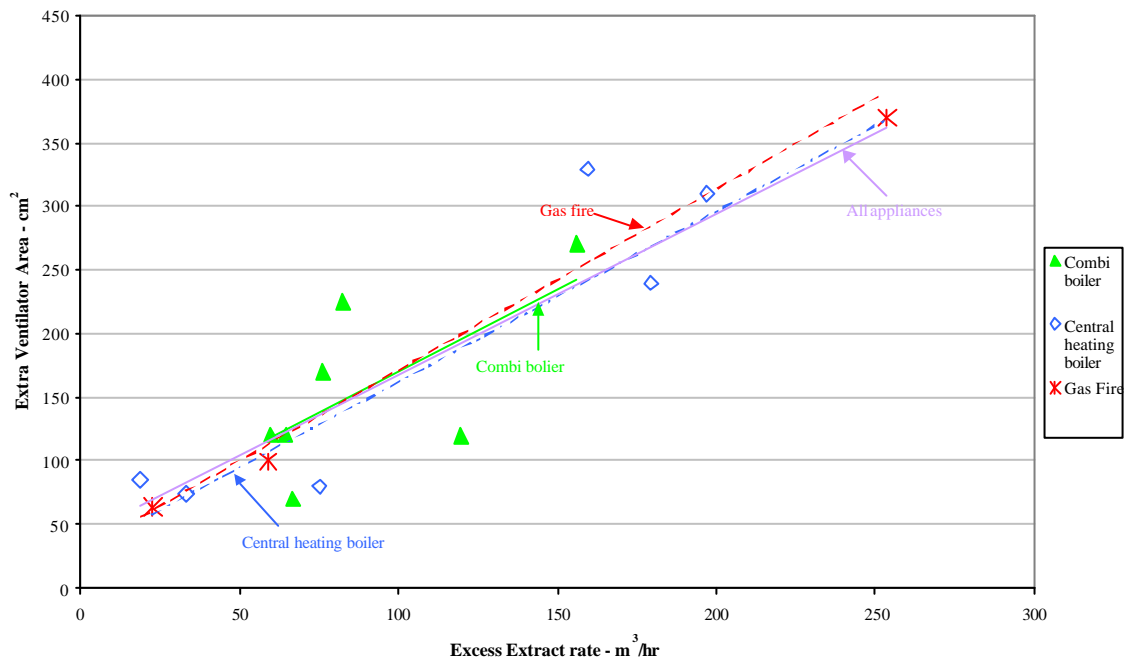


Figure 25. Extra ventilator area required to cause normal flow in the flue v. excess flow rate in extraction system

APPENDIX A COLLECTED FIGURES FOR TESTS 1 TO 21

Similar figures are presented for each test, with the following nomenclature for the figures

Note: (# is the test number)

- Triplet (CO, CO₂ and O₂) of Room 1 concentration profile time series, captioned as:

Figure A#(a)
Test #, Concentration profiles in Room 1

- Triplet (CO, CO₂ and O₂) of extract concentration plots vs. time, captioned as:

Figure A#(b)
Test #, Concentration in the extract system

- Triplet (CO, CO₂ and O₂) of flue and air supply concentrations vs. time, captioned as:

Figure A#(c)
Test #, Concentration in the flue, and in the combustion air supply

- Wind speed vs. time and polar plot of speed and direction, captioned as:

Figure A#(d)
Test #, Wind speed and direction

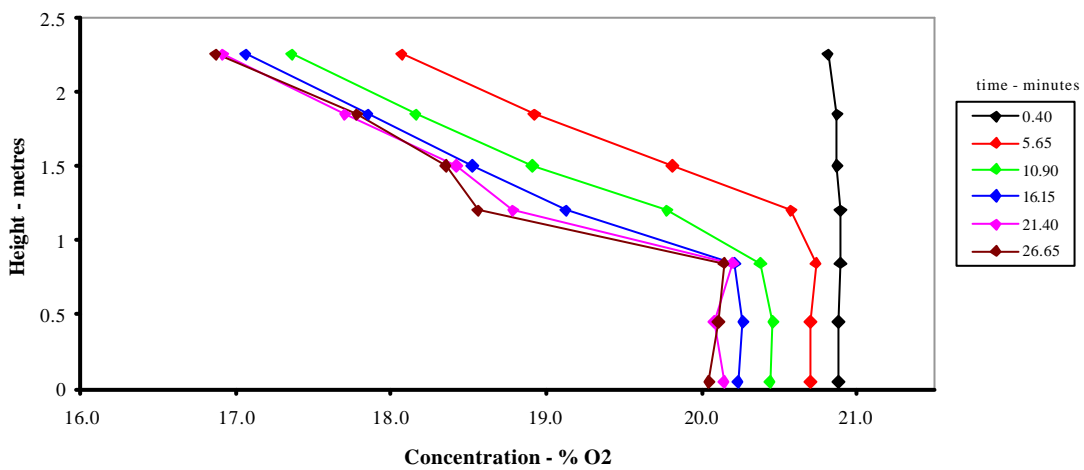
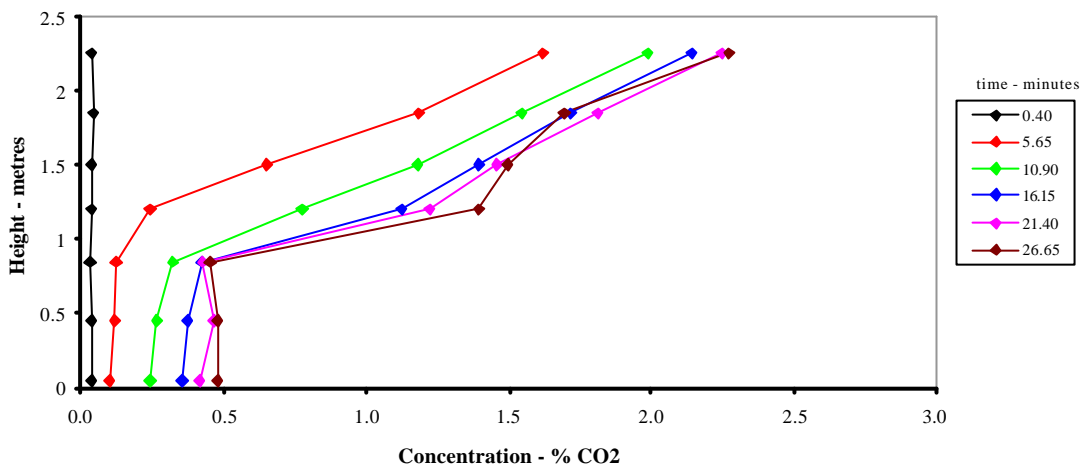
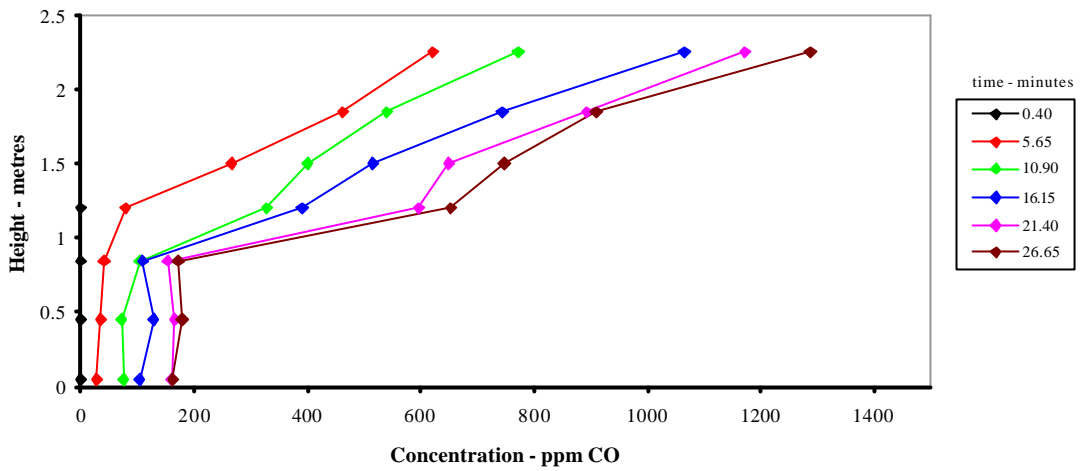


Figure A1(a)
Test 1. Concentration profiles in Room 1

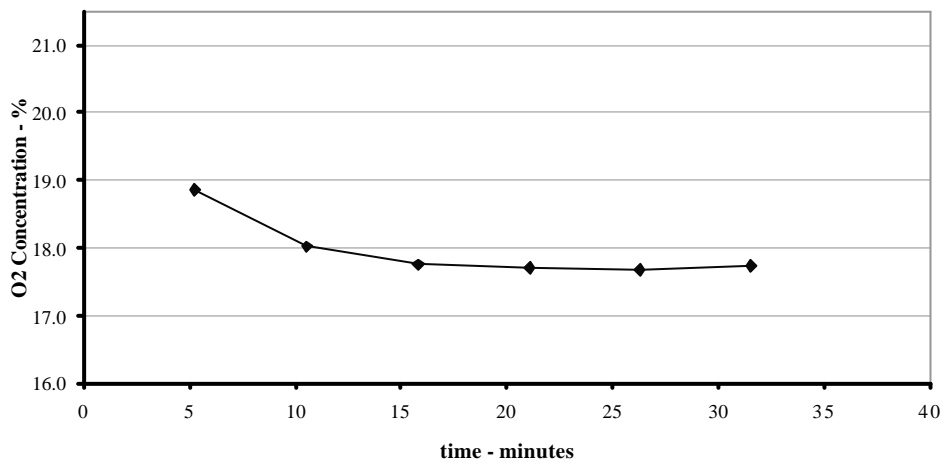
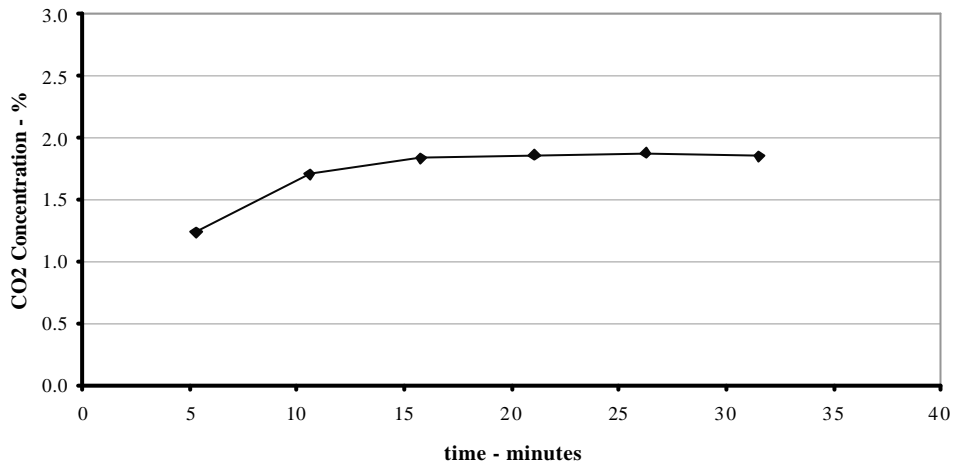
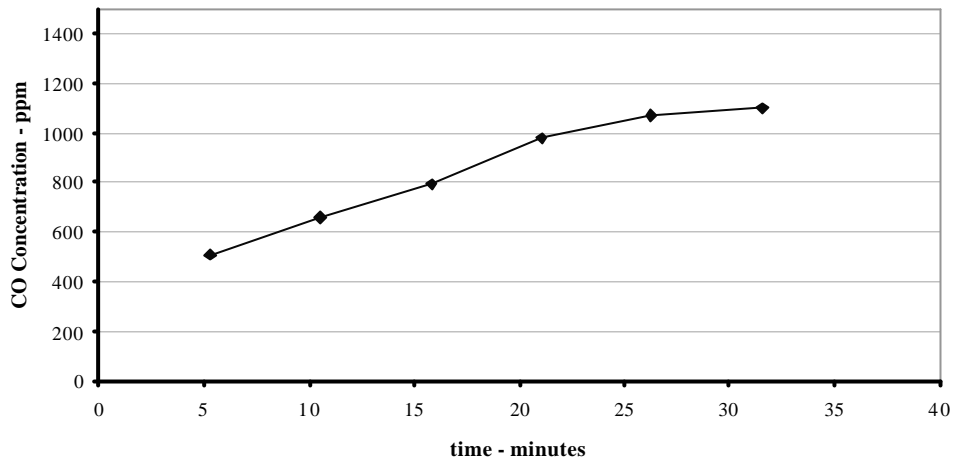


Figure A1(b)
Test 1. Concentration in the extract system

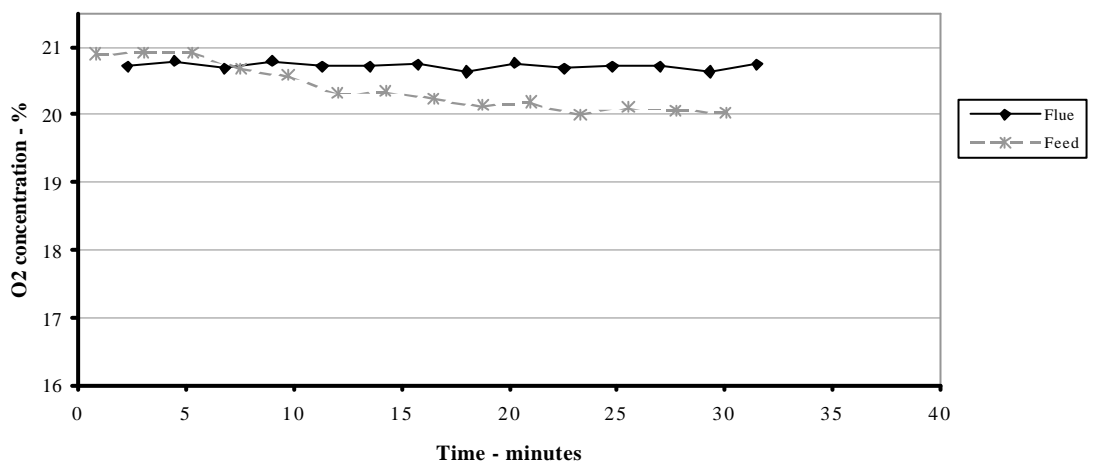
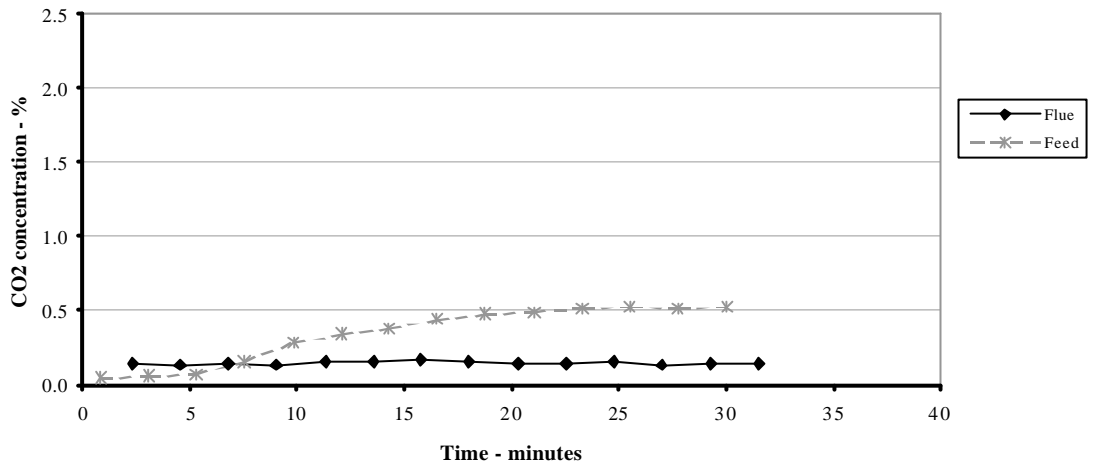
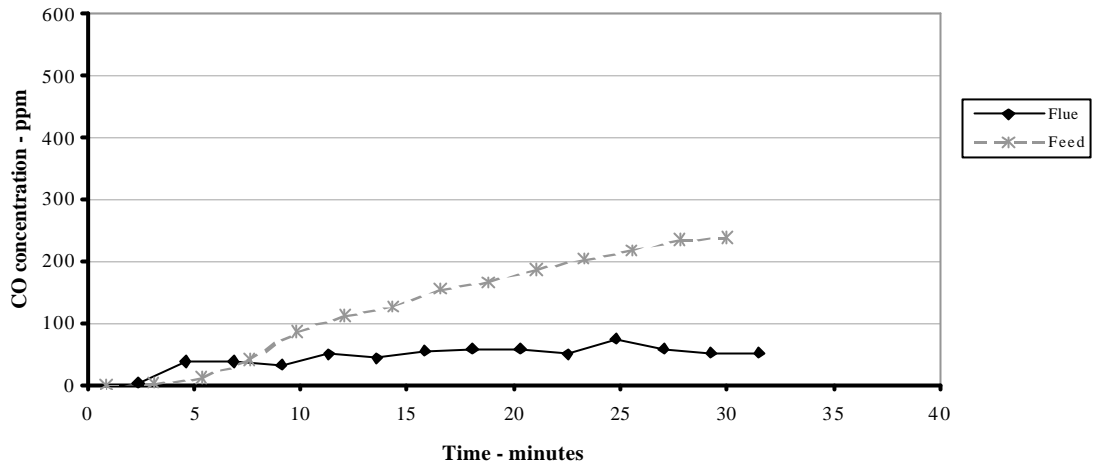


Figure A1(c)
Test 1. Concentration in the flue, and in the combustion air supply

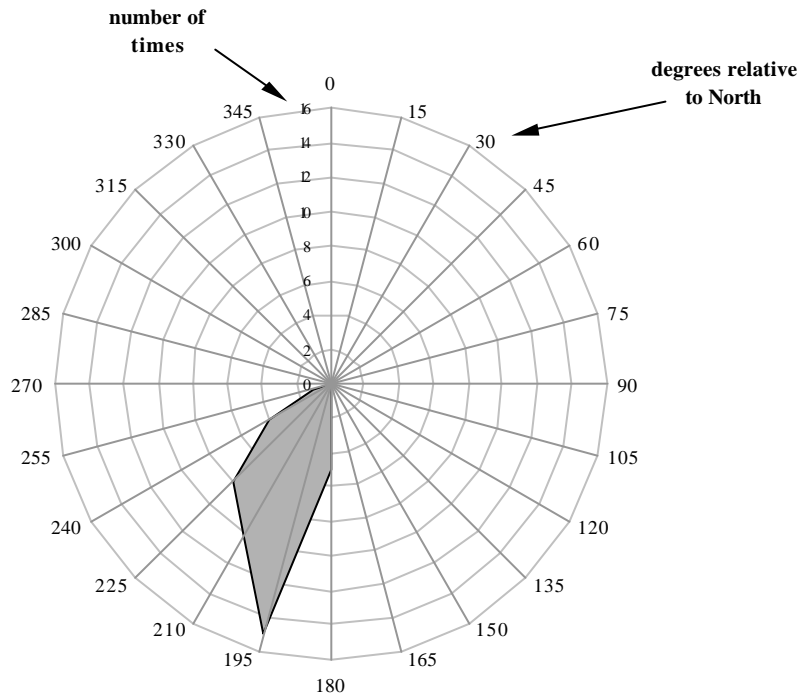
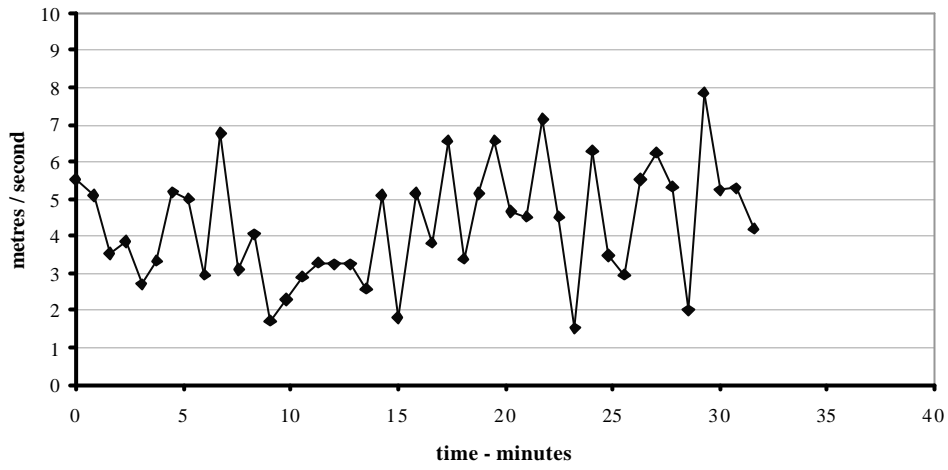


Figure A1(d)
Test 1. Wind speed and direction

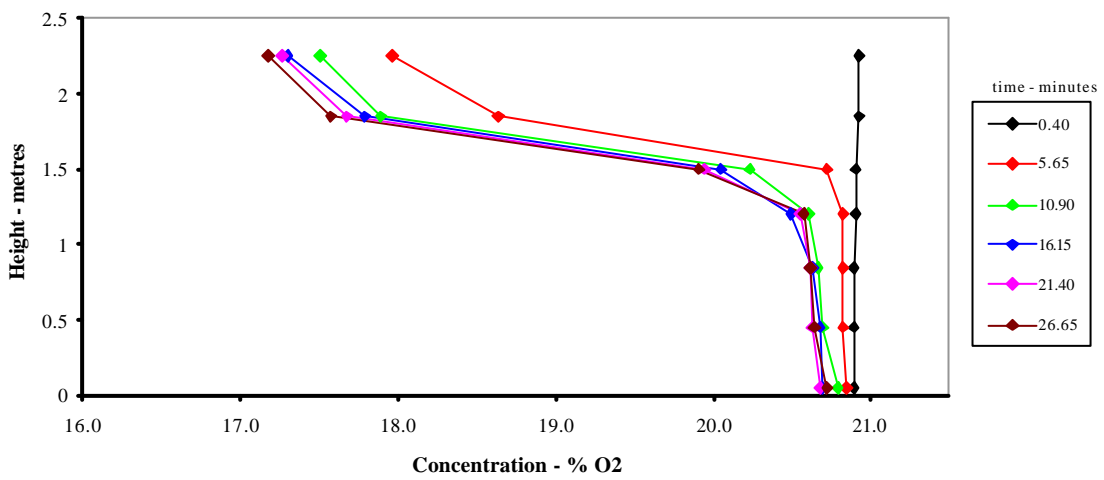
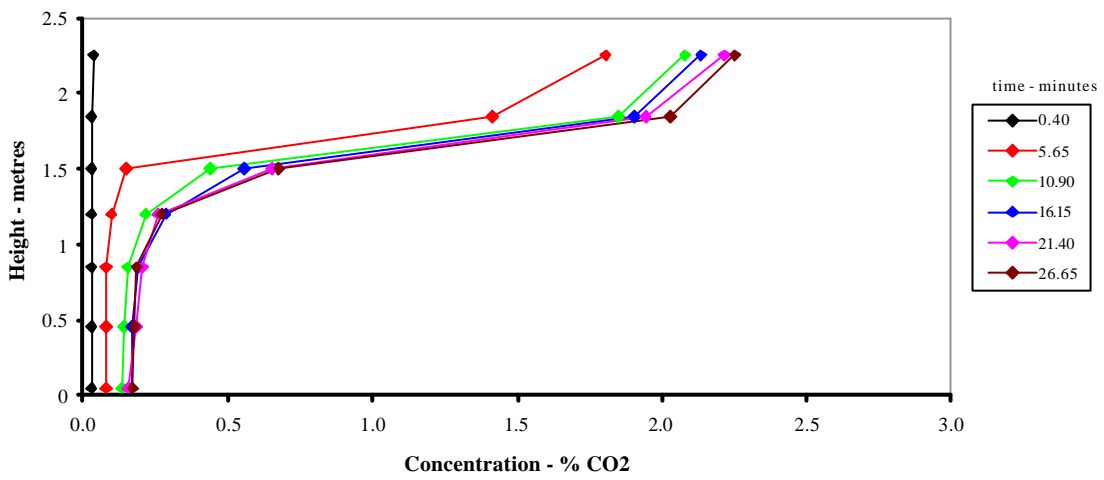
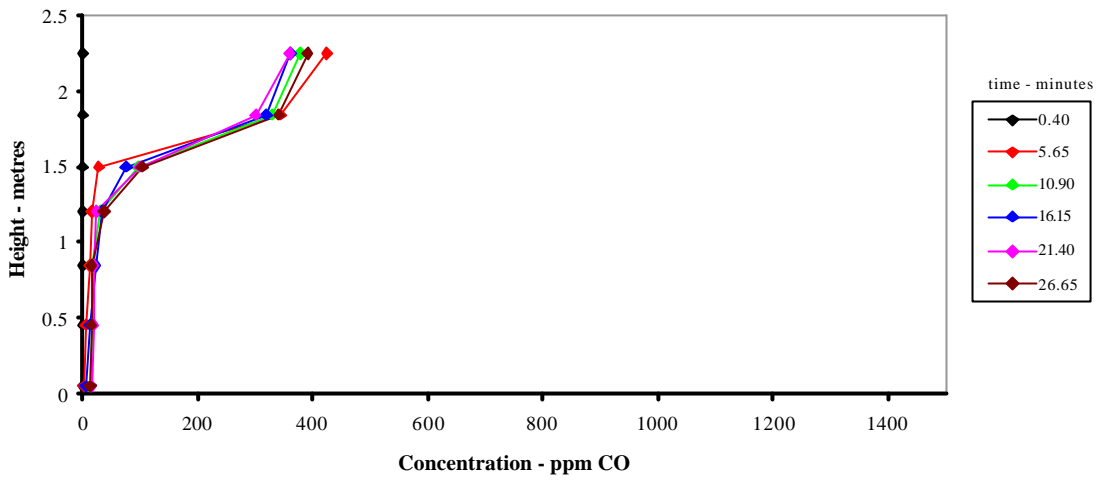


Figure A2(a)
Test 2. Concentration profiles in Room 1

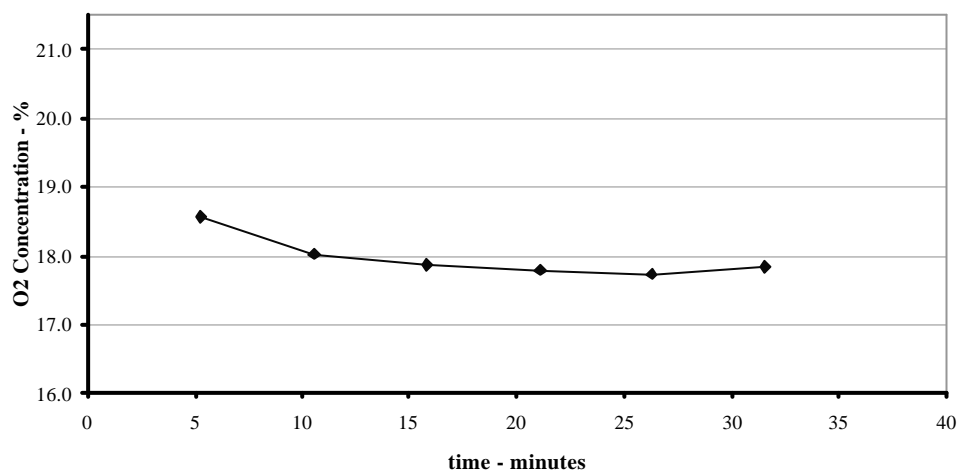
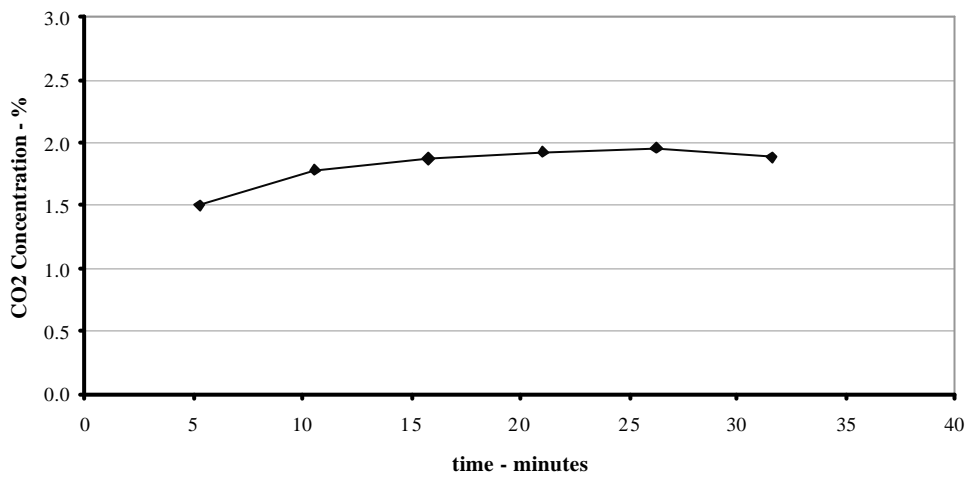
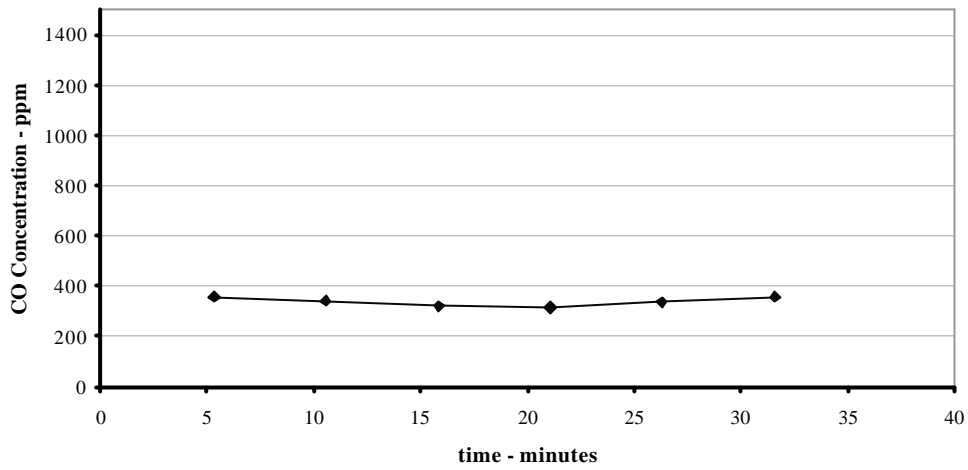


Figure A2(b)
Test 2. Concentration in the extract system

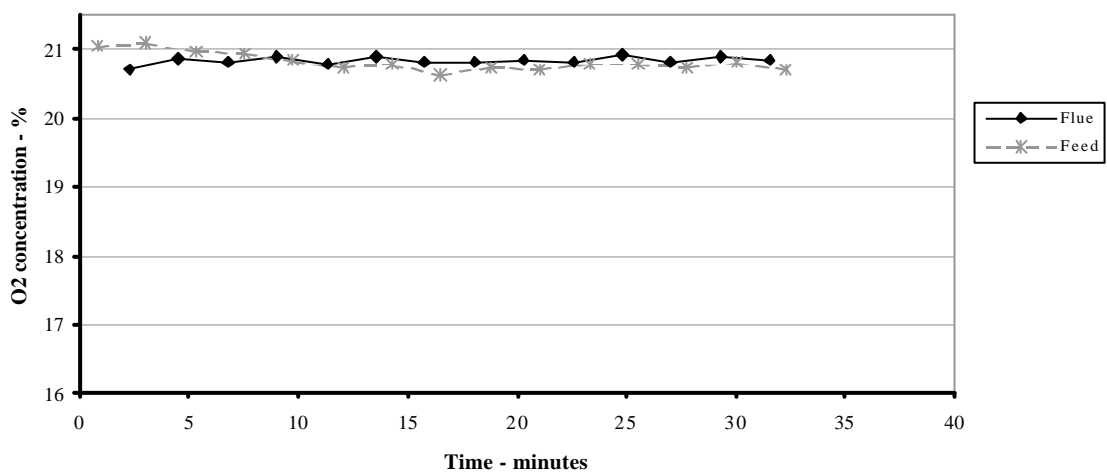
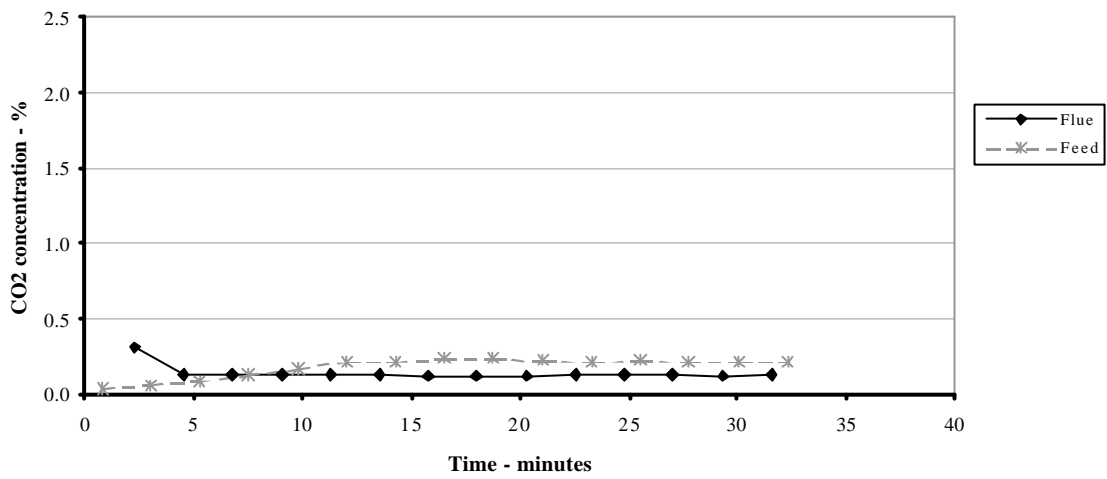
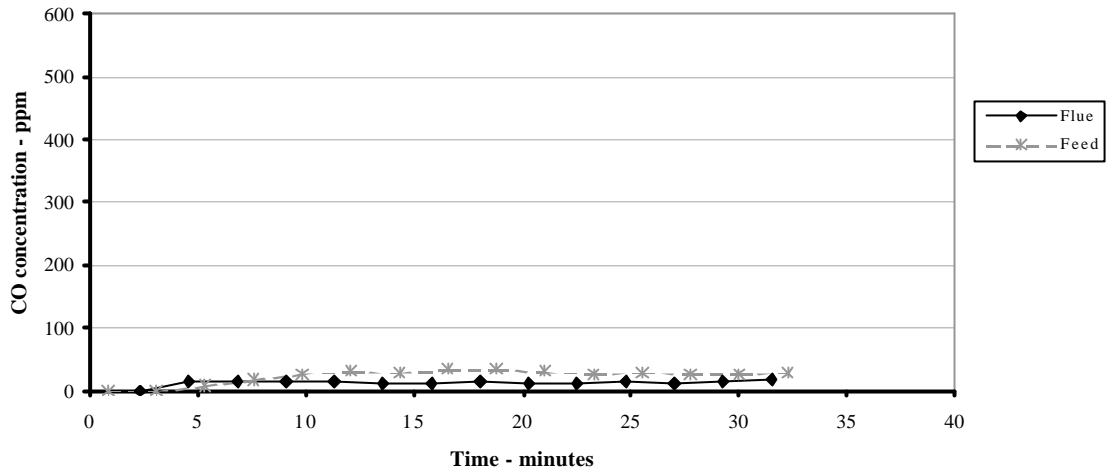


Figure A2(c)
Test 2. Concentration in the flue, and in the combustion air supply

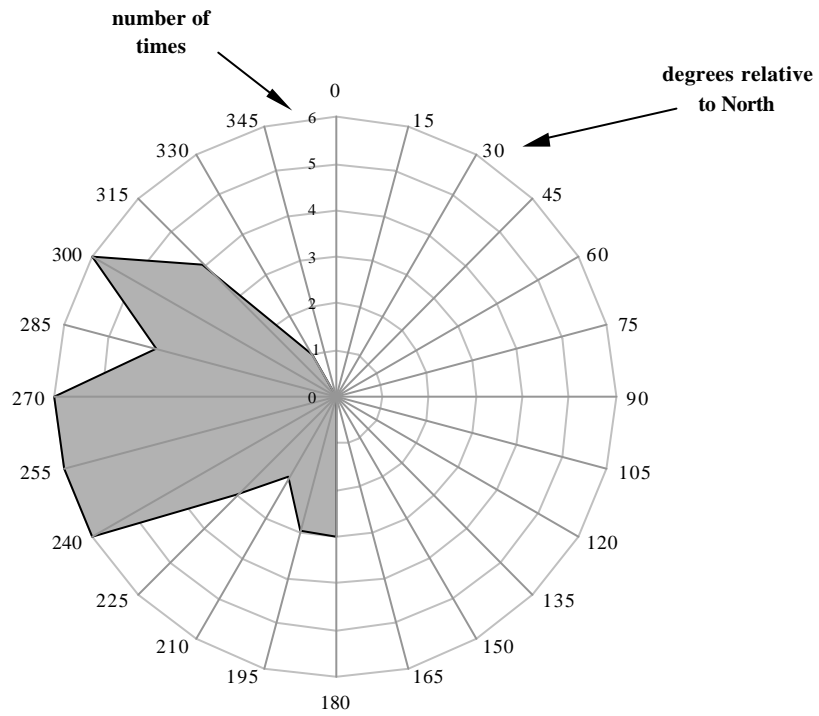
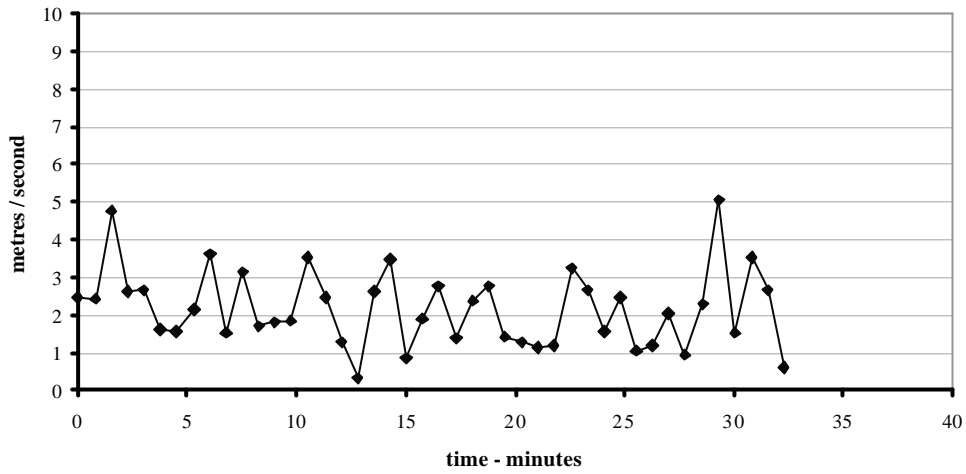


Figure A2(d)
Test 2. Wind speed and direction

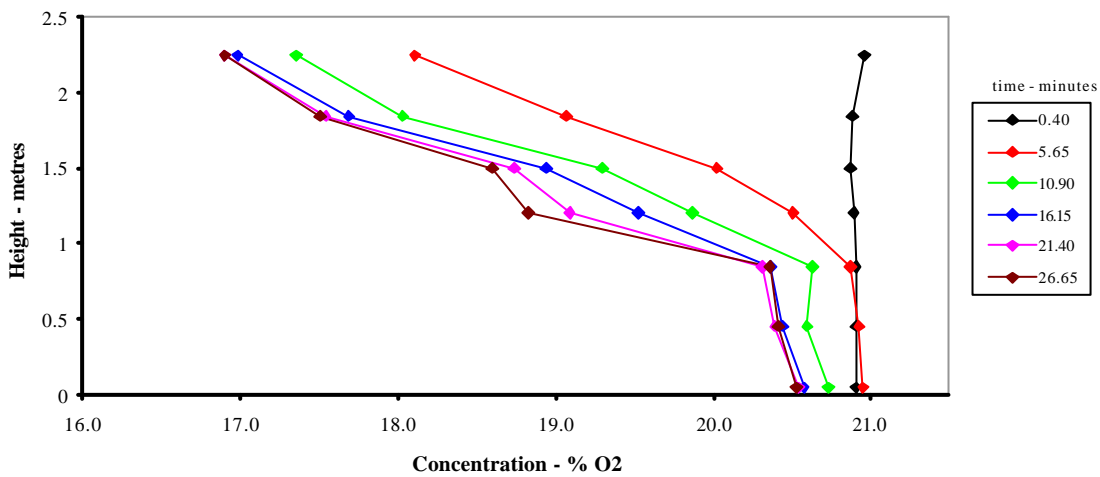
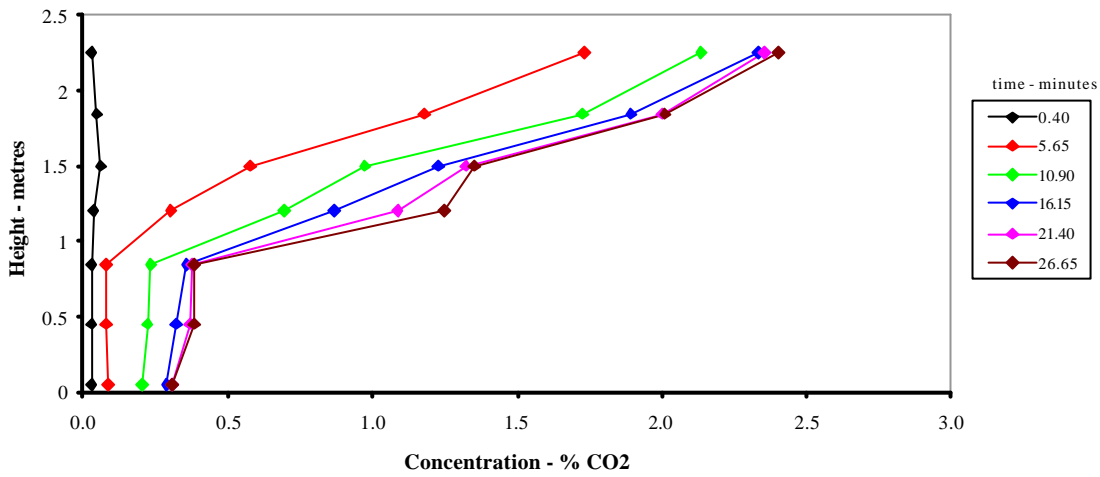
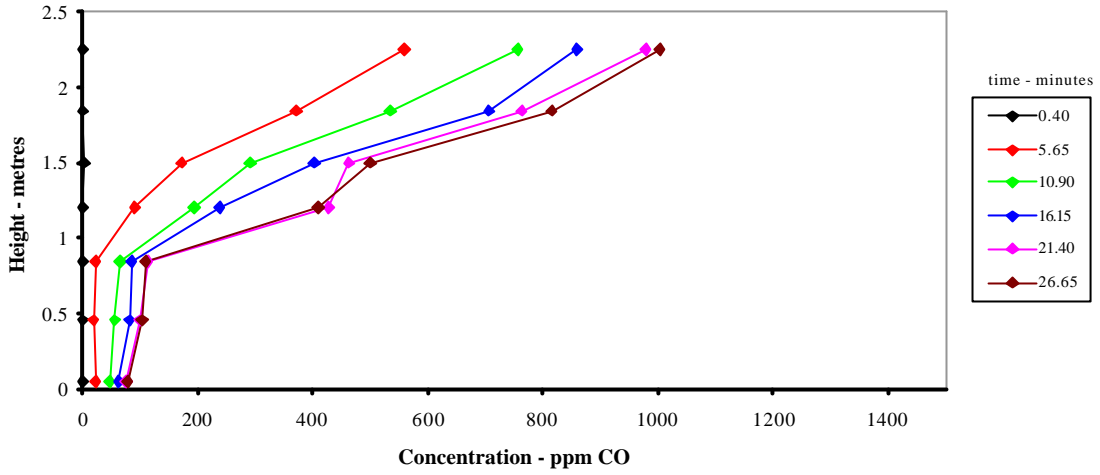


Figure A3(a)
Test 3. Concentration profiles in Room 1

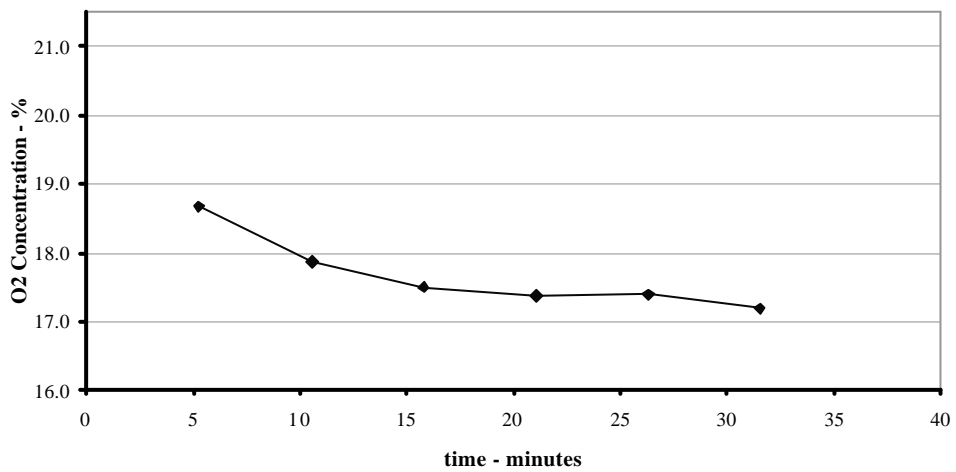
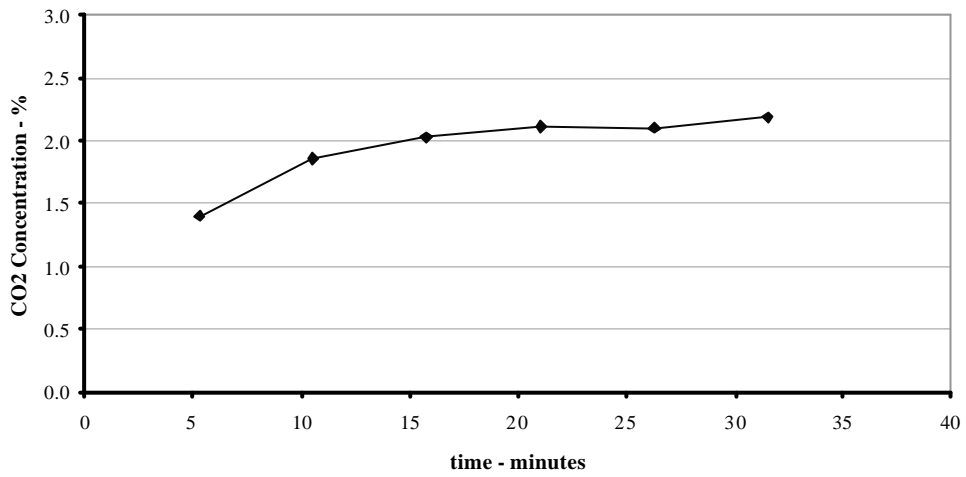
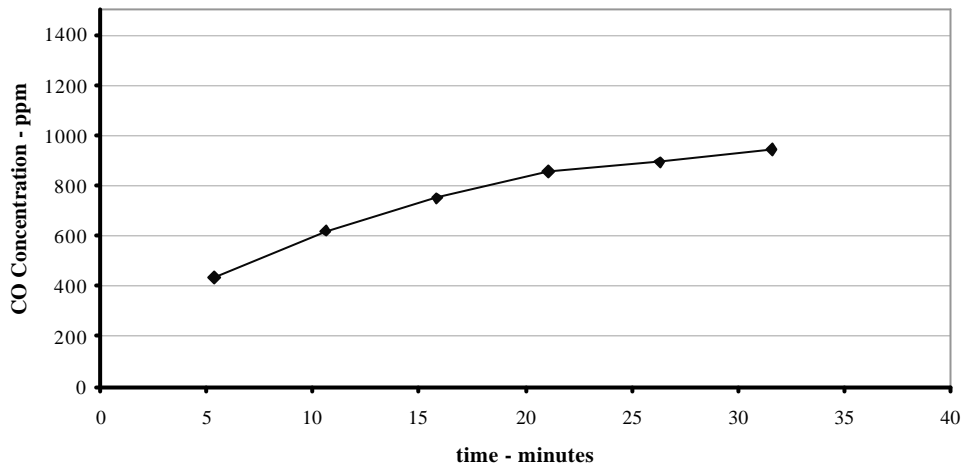


Figure A3(b)
Test 3. Concentration in the extract system

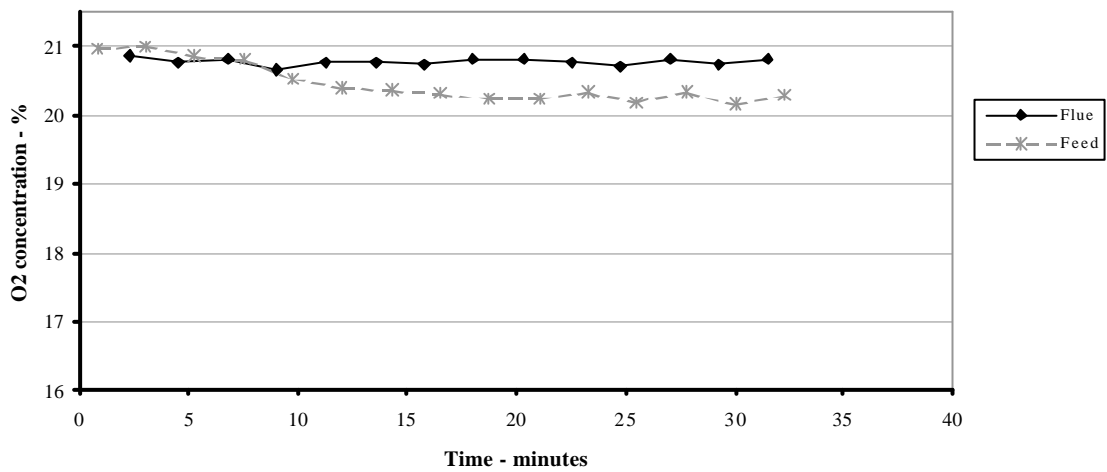
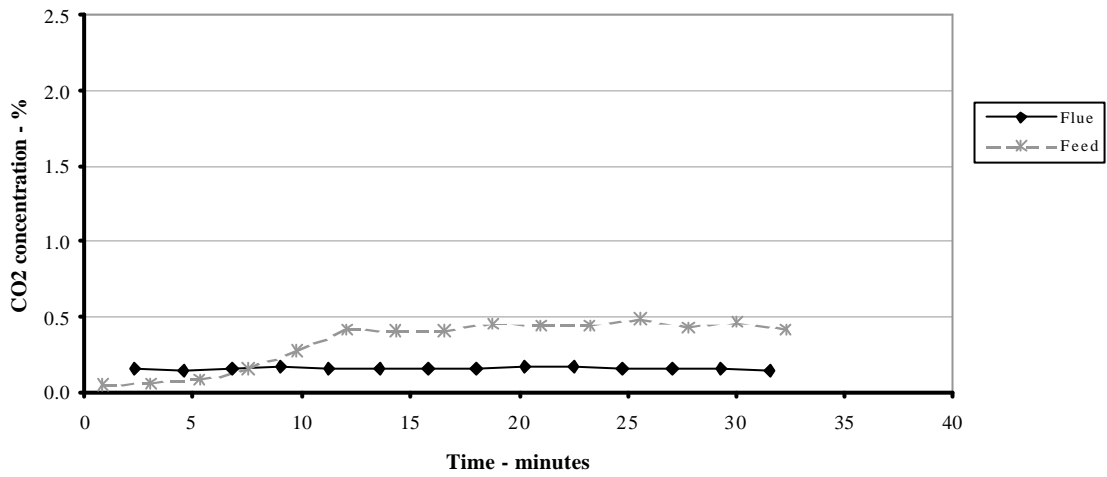
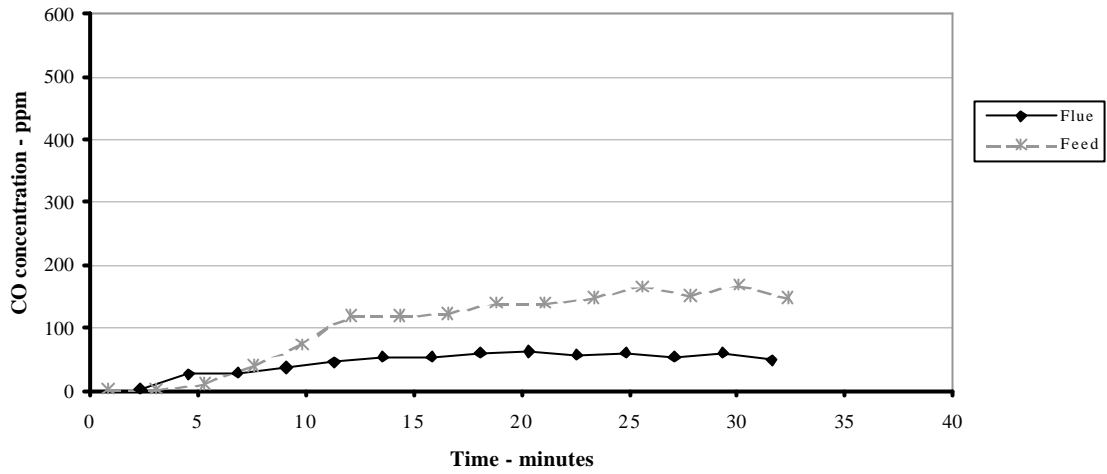


Figure A3(c)
Test 3. Concentration in the flue, and in the combustion air supply

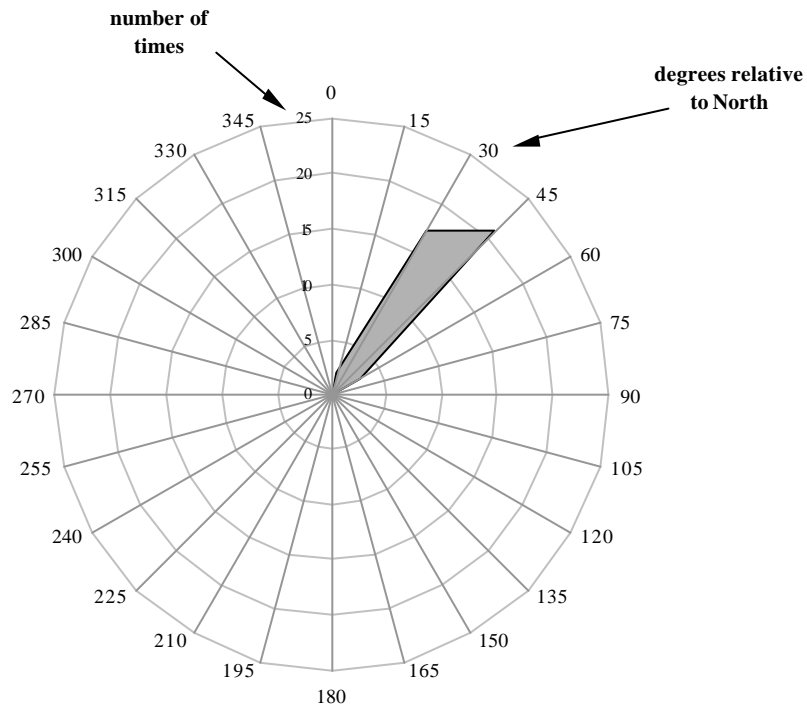
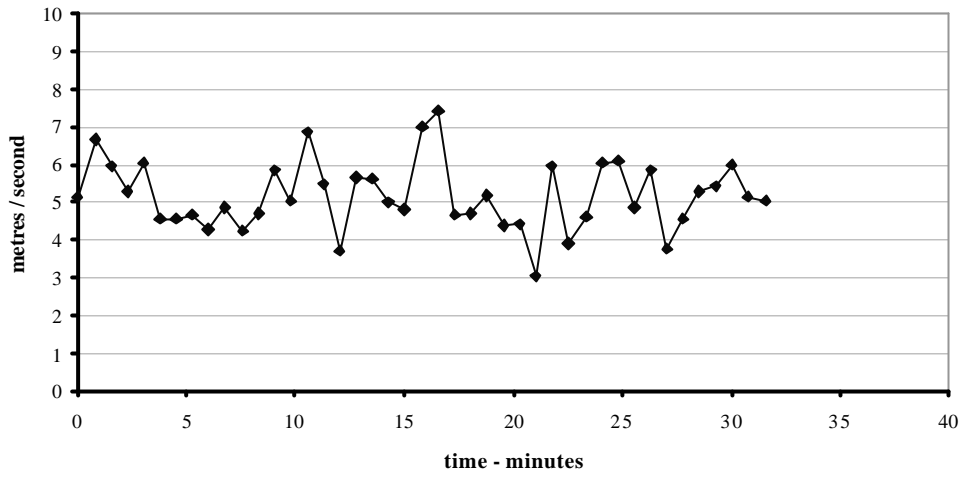


Figure A3(d)
Test 3. Wind speed and direction

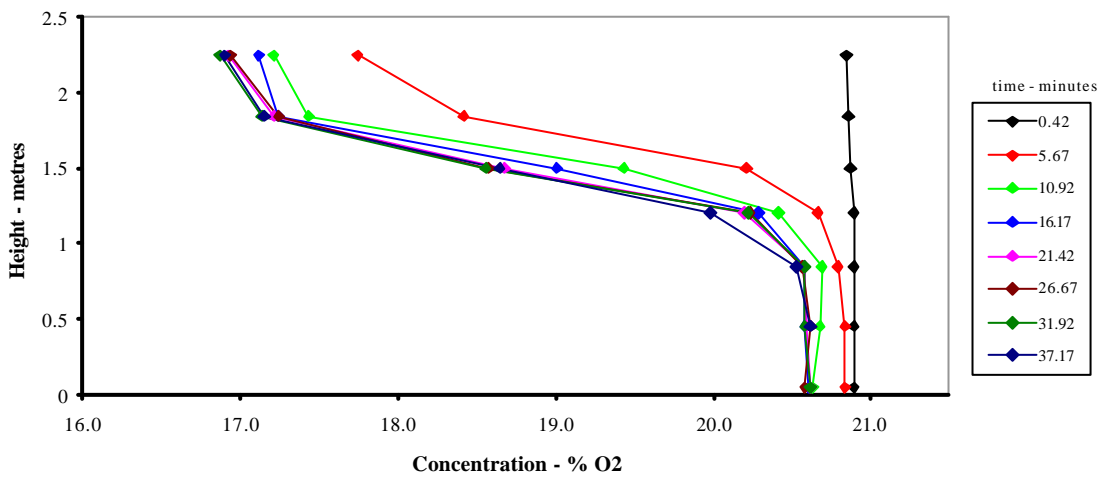
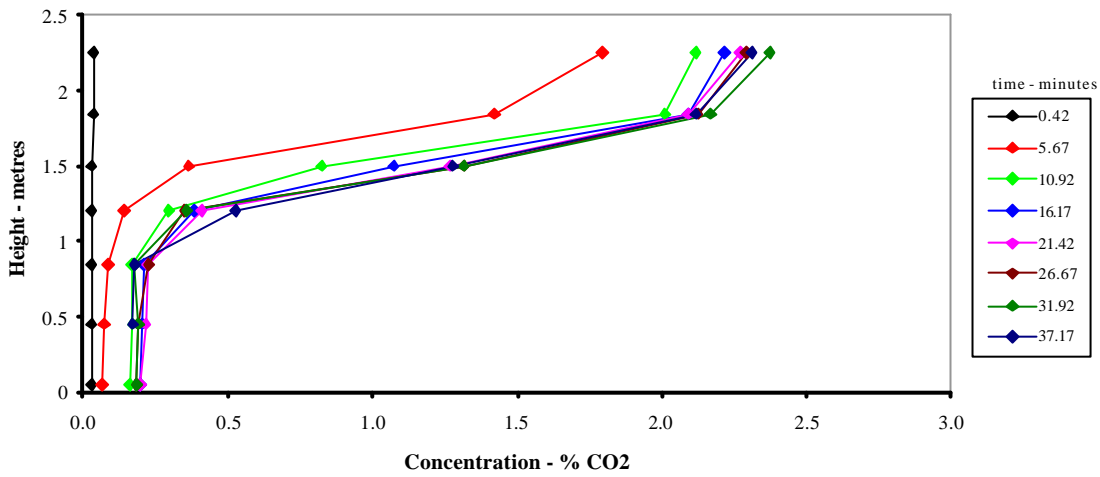
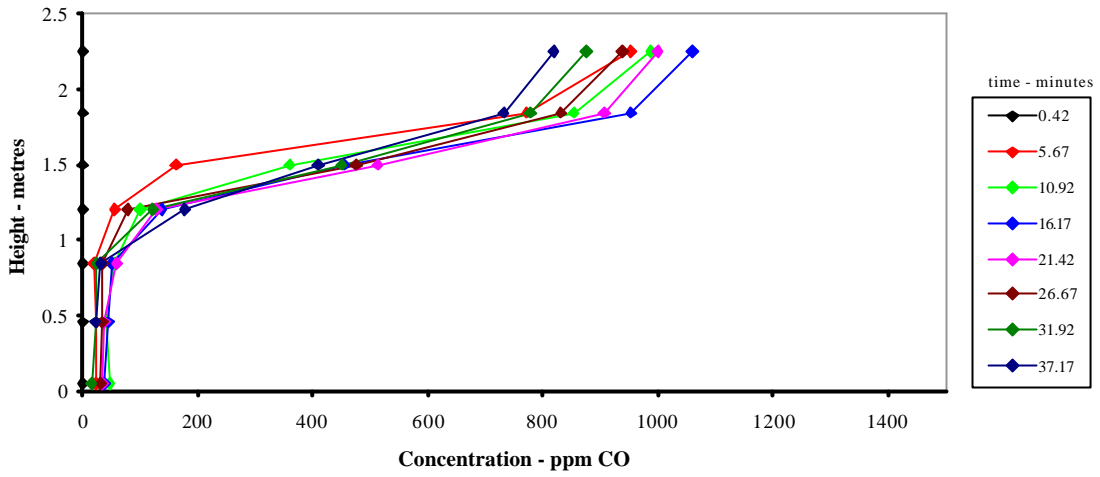


Figure A4(a)
Test 4. Concentration profiles in Room 1

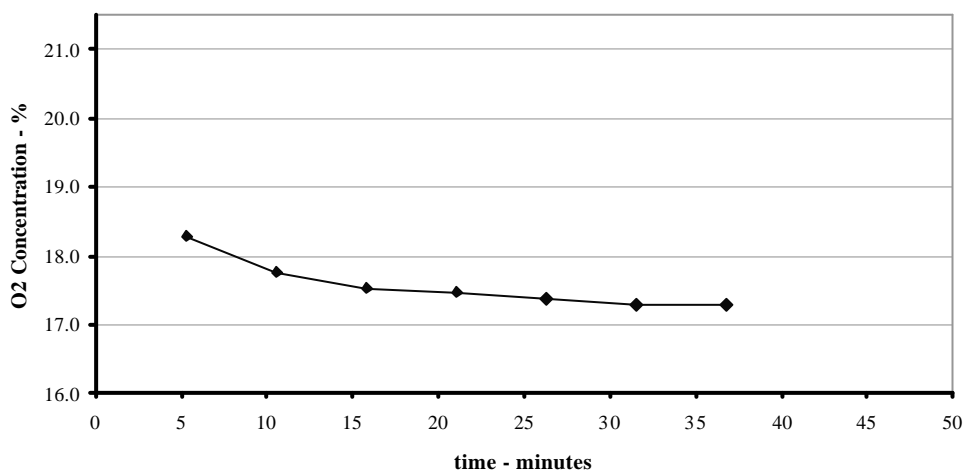
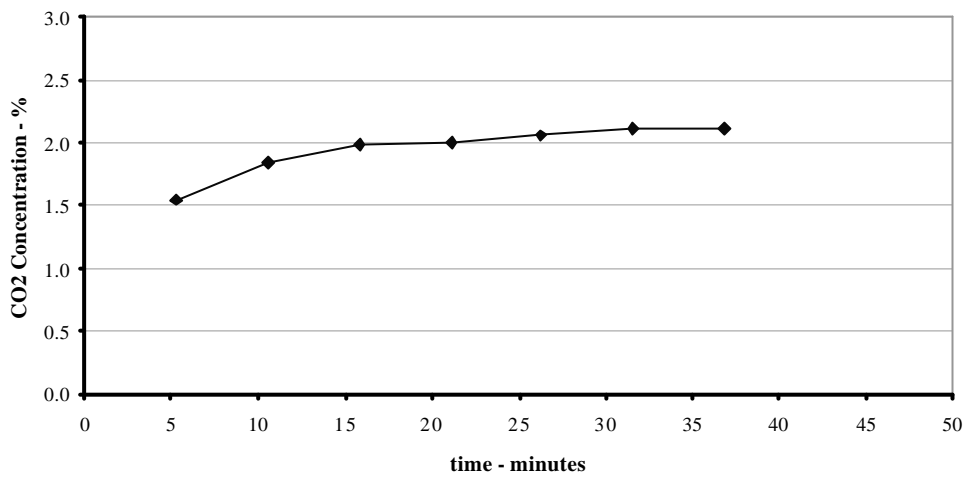
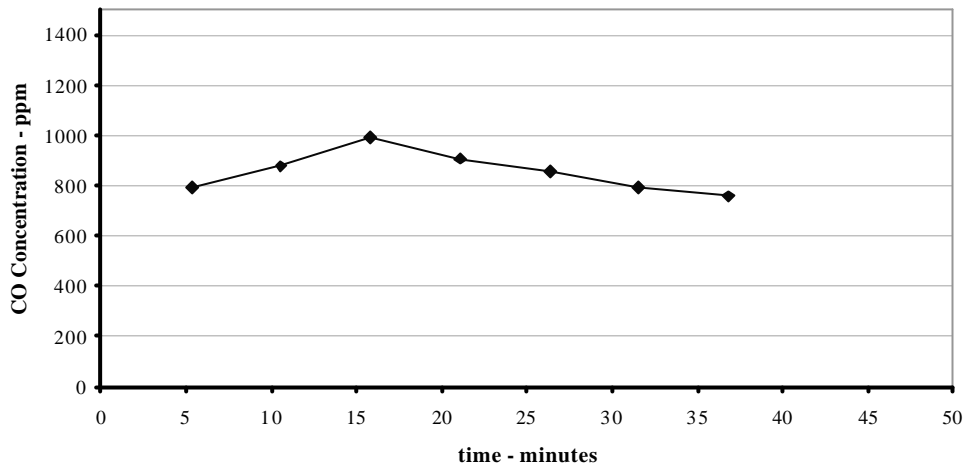


Figure A4(b)
Test 4. Concentration in the extract system

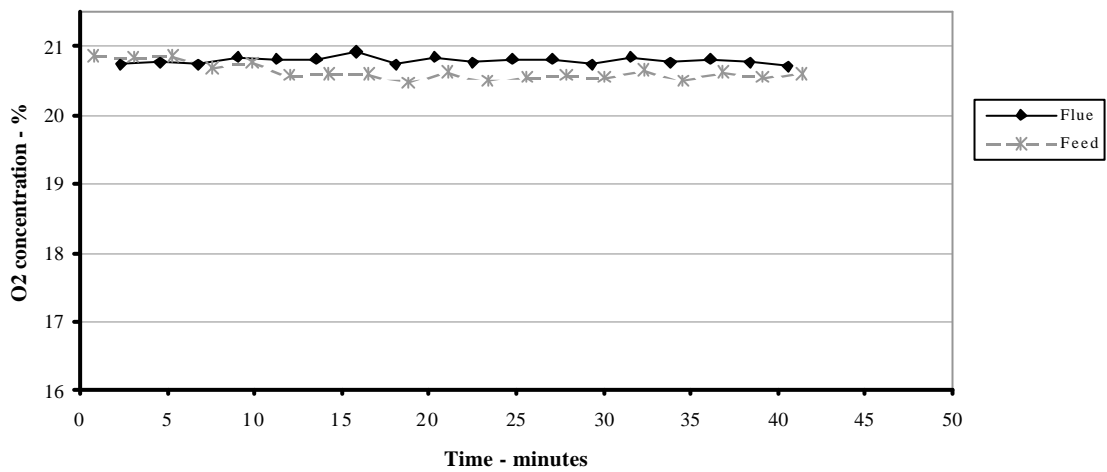
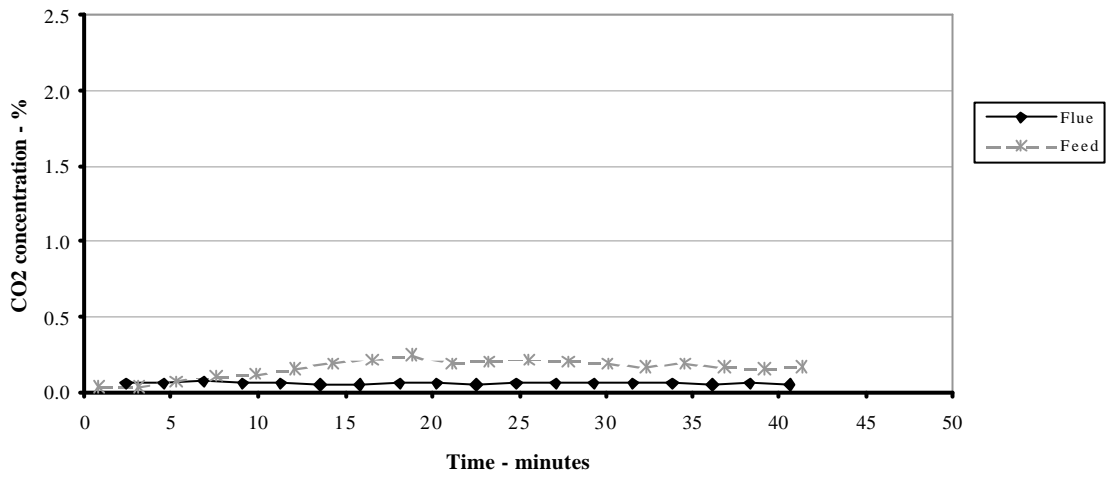
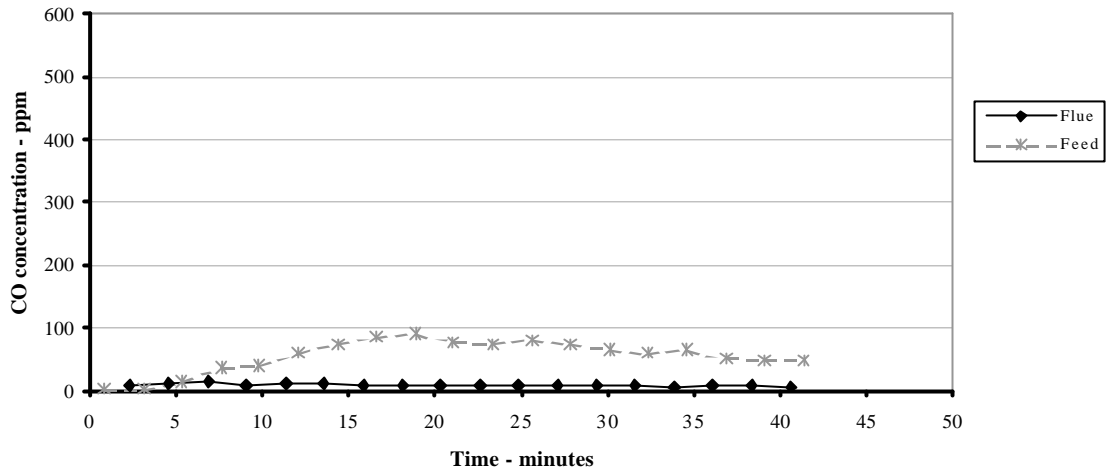


Figure A4(c)
Test 4. Concentration in the flue, and in the combustion air supply

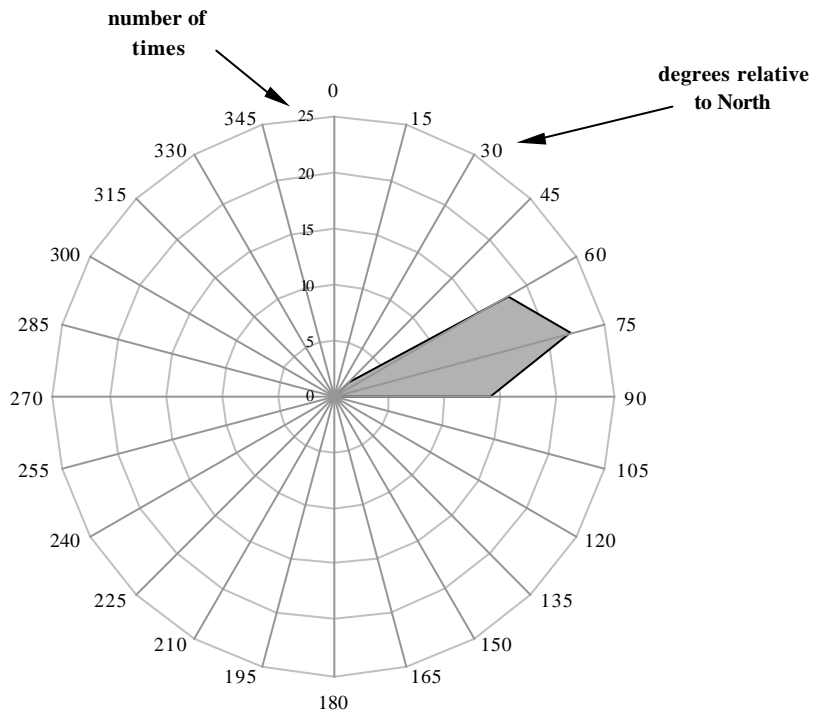
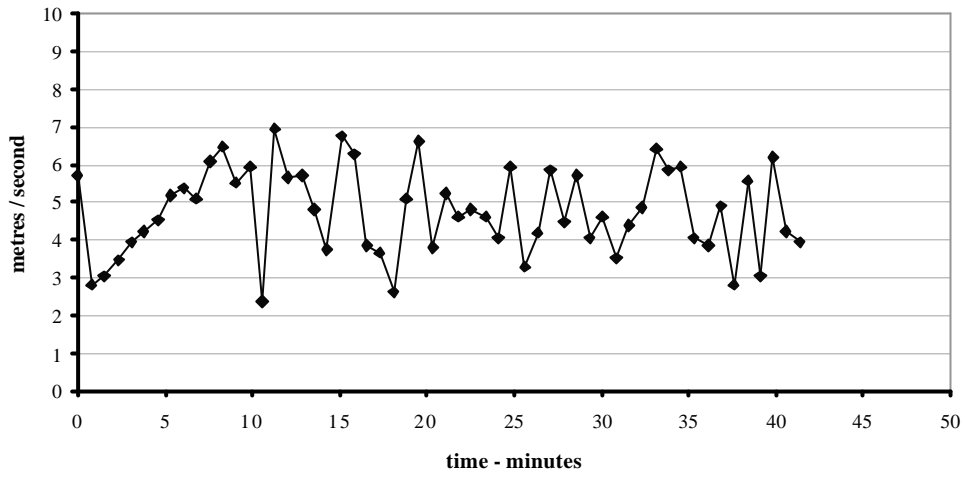


Figure A4(d)
Test 4. Wind speed and direction

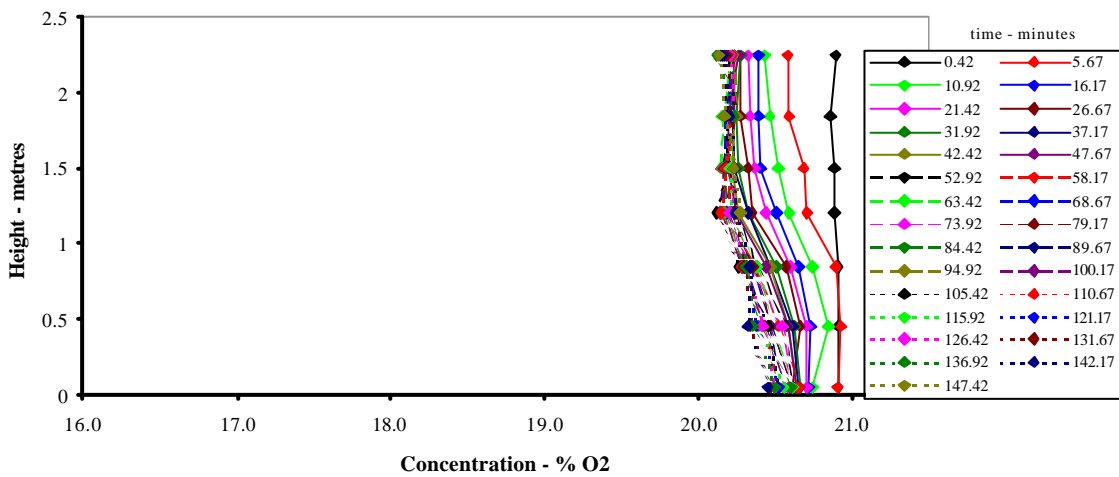
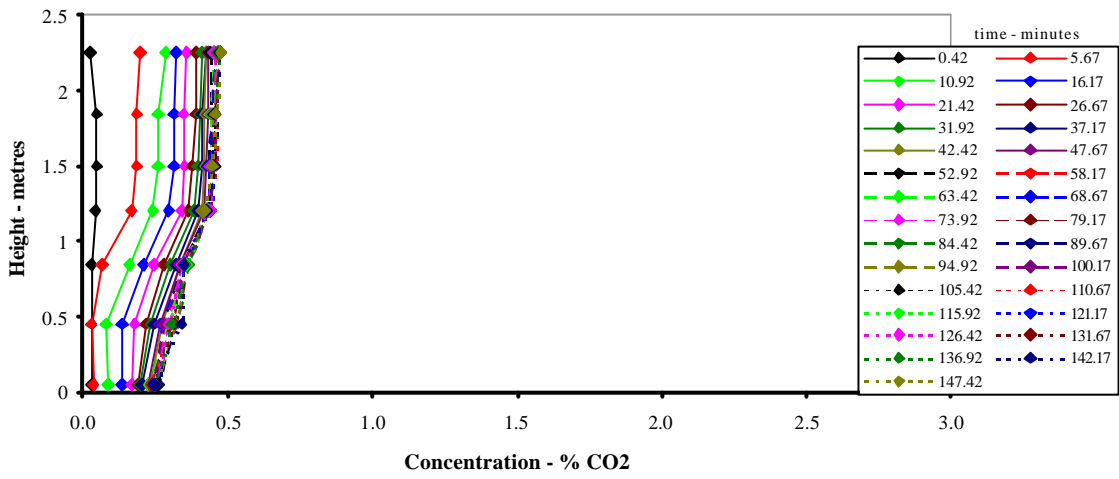
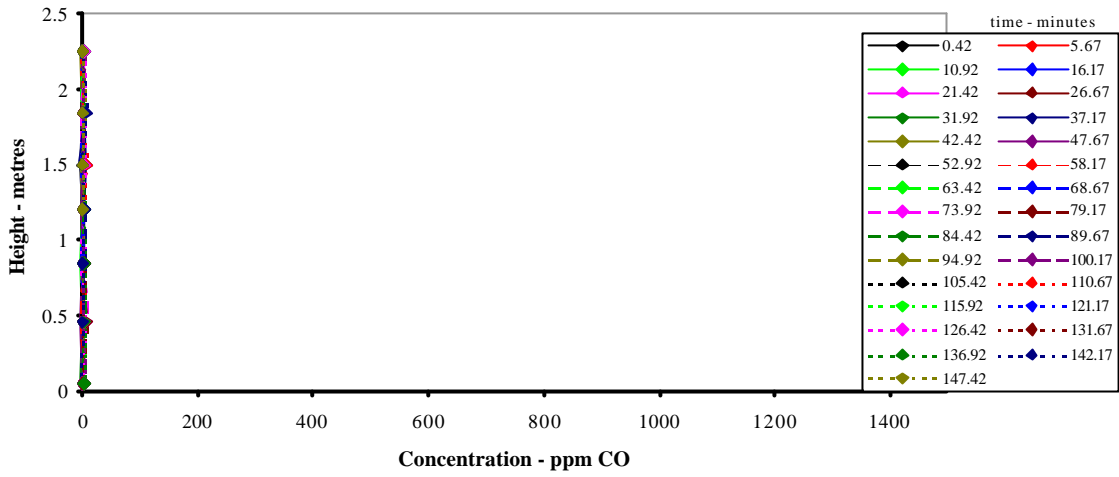


Figure A5(a)
Test 5. Concentration profiles in Room 1

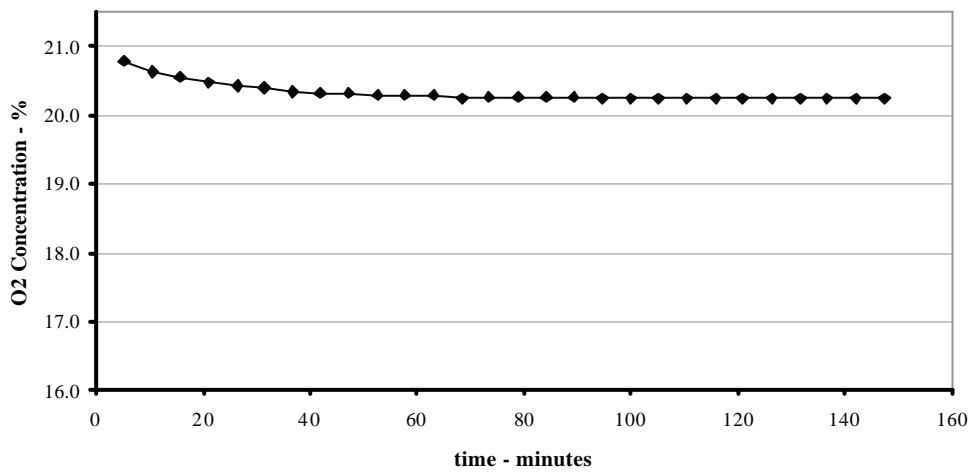
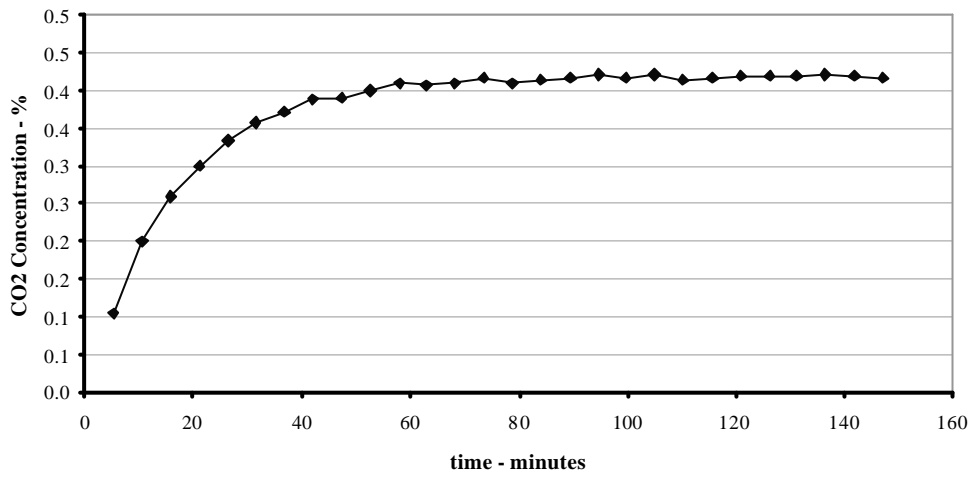
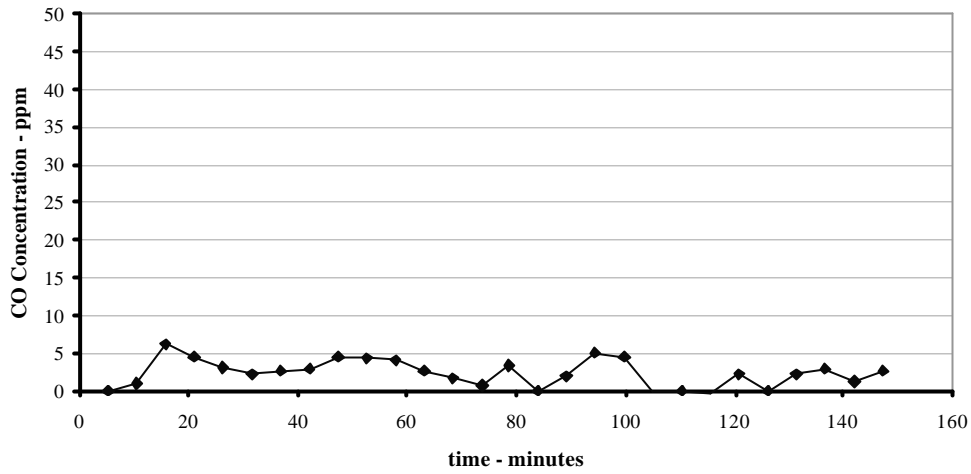


Figure A5(b)
Test 5. Concentration in the extract system

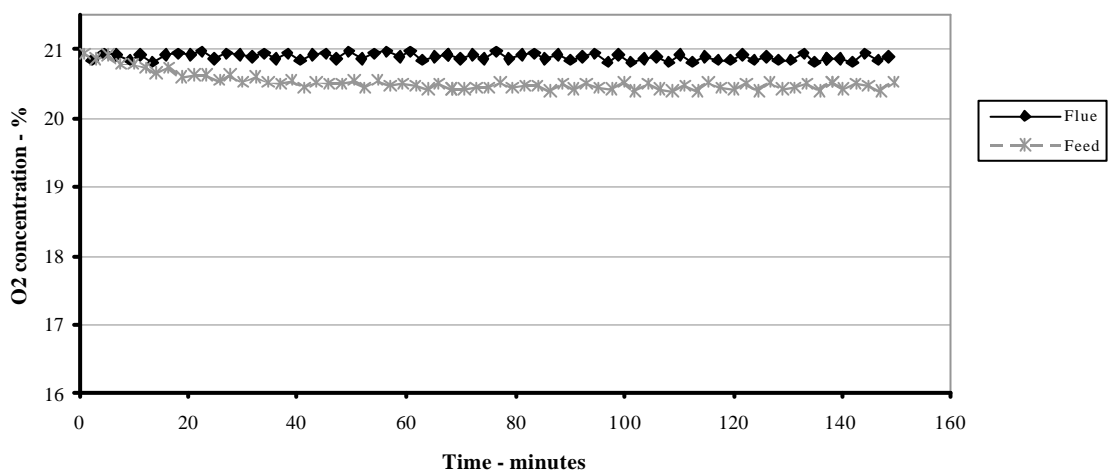
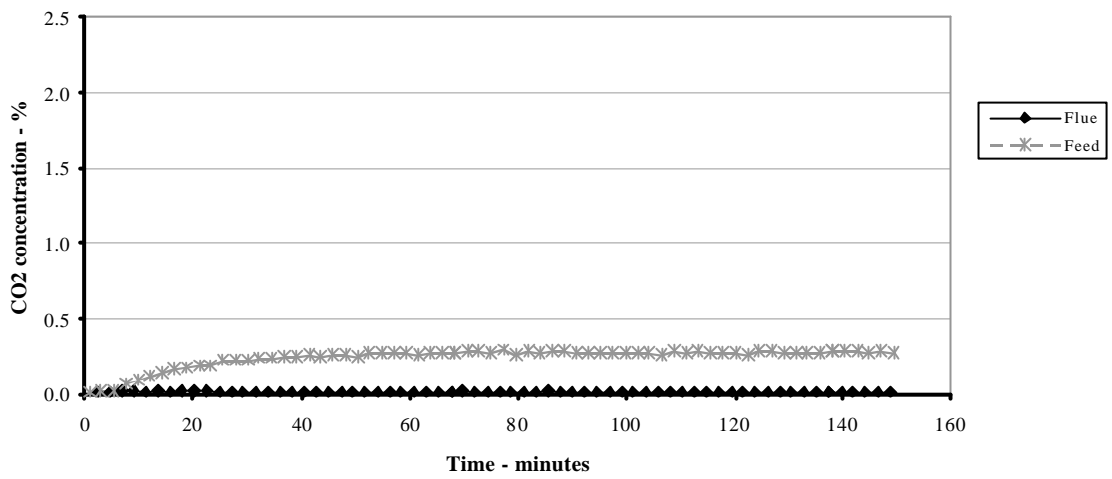
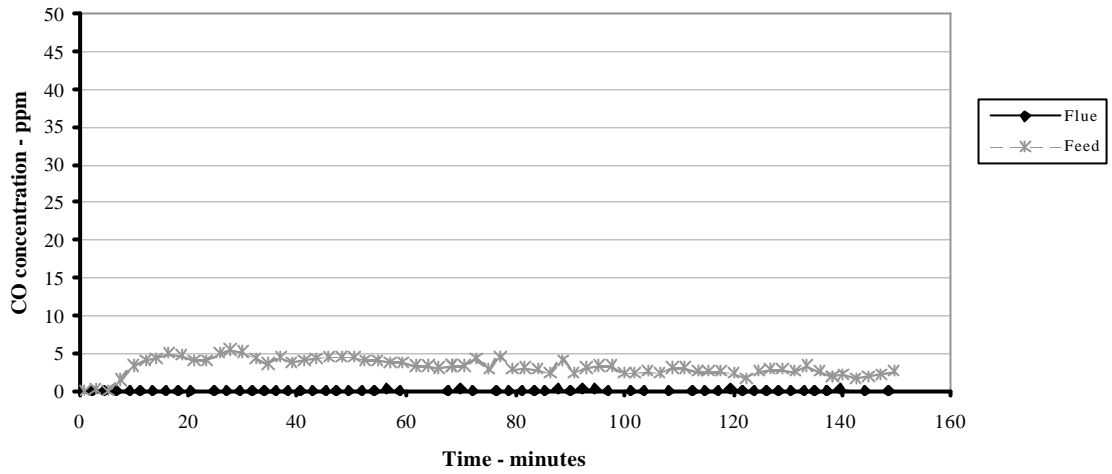


Figure A5(c)
Test 5. Concentration in the flue, and in the combustion air supply

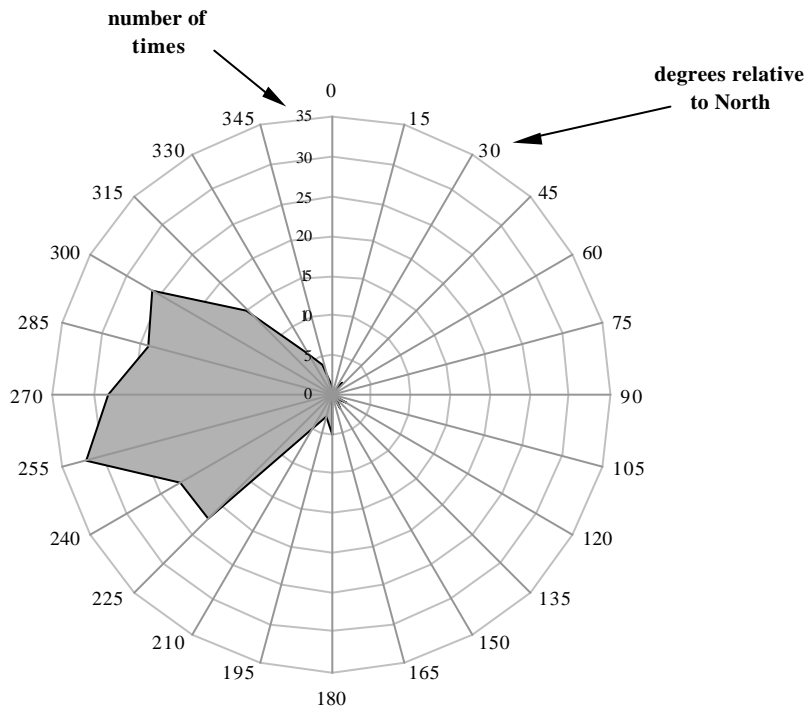
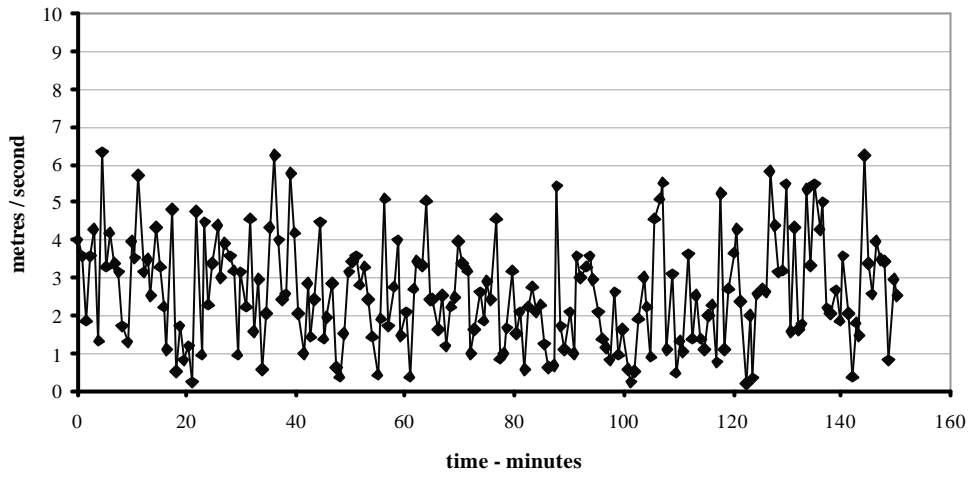


Figure A5(d)
Test 5. Wind speed and direction

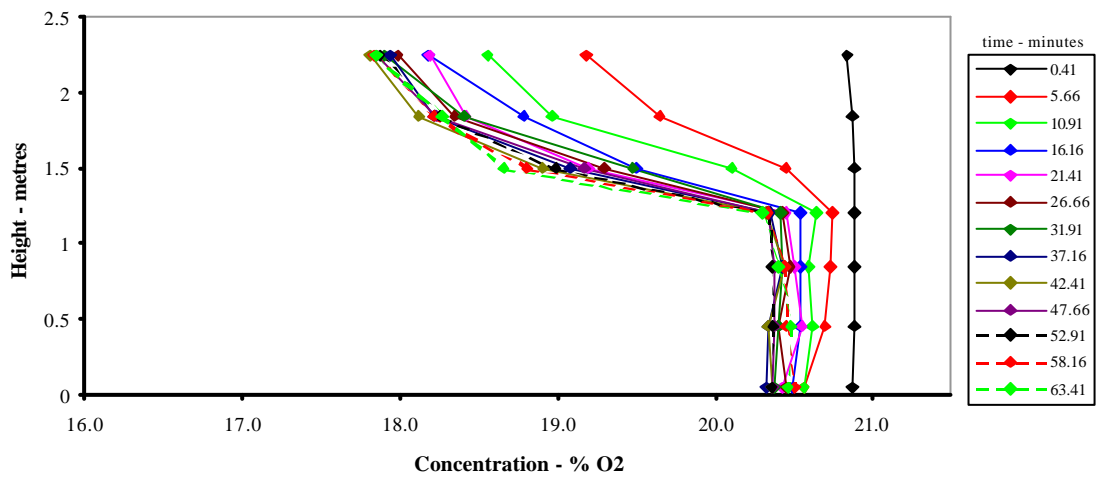
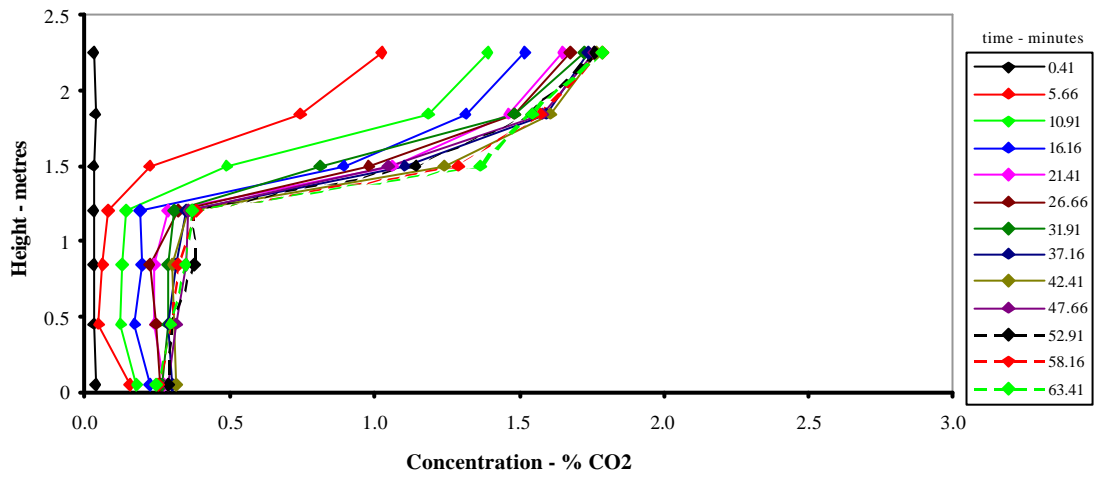
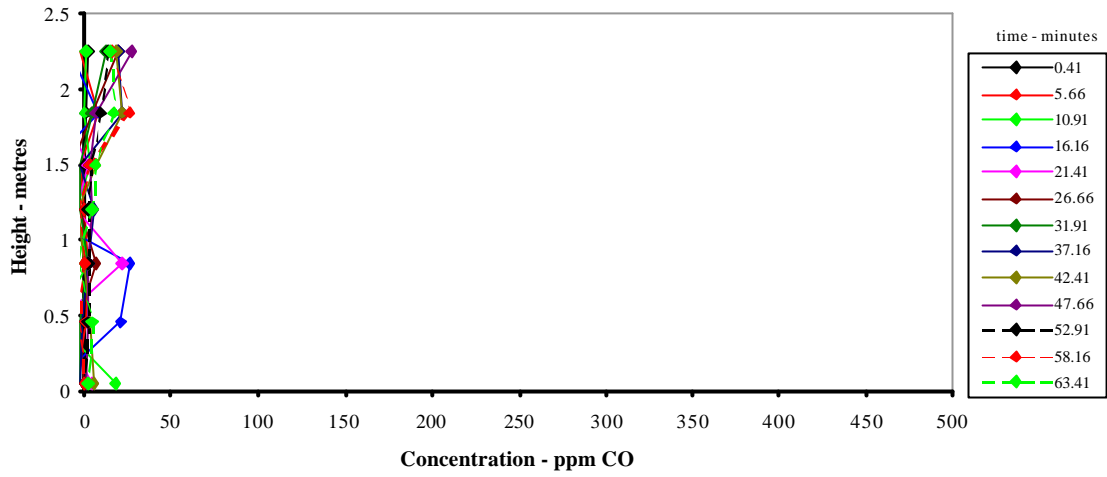


Figure A6(a)
Test 6. Concentration profiles in Room 1

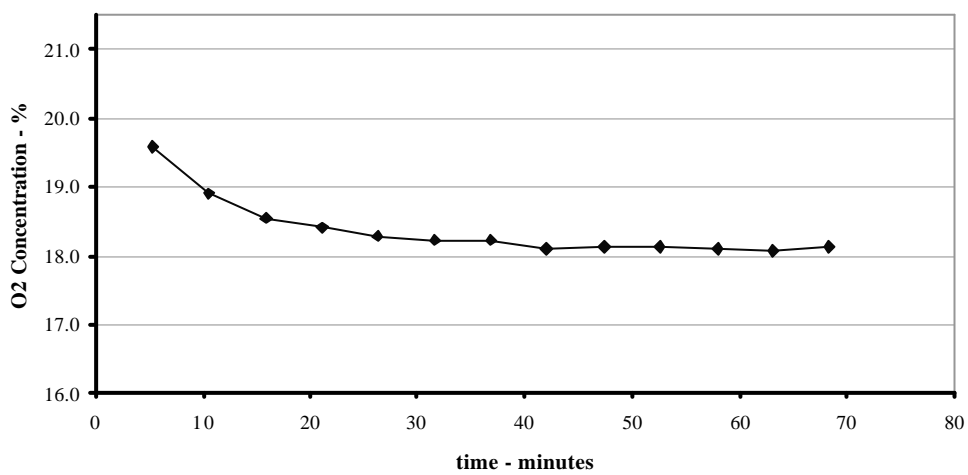
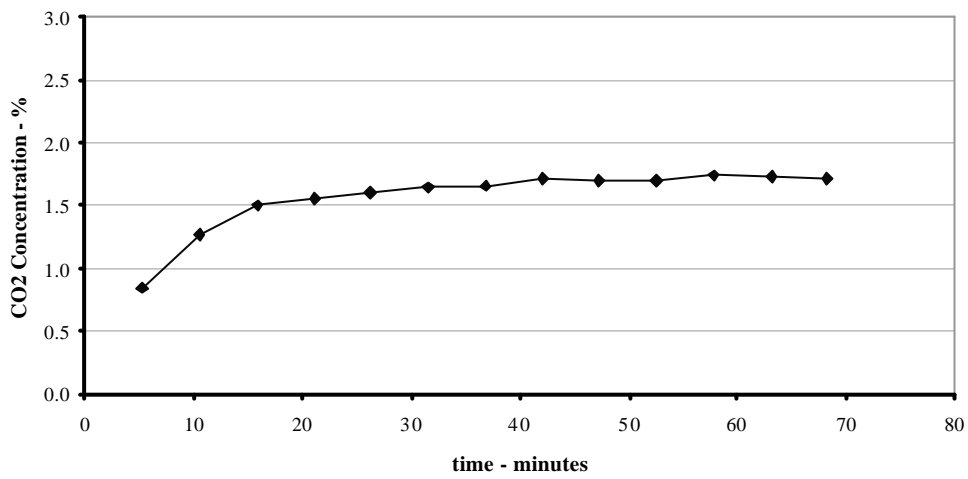
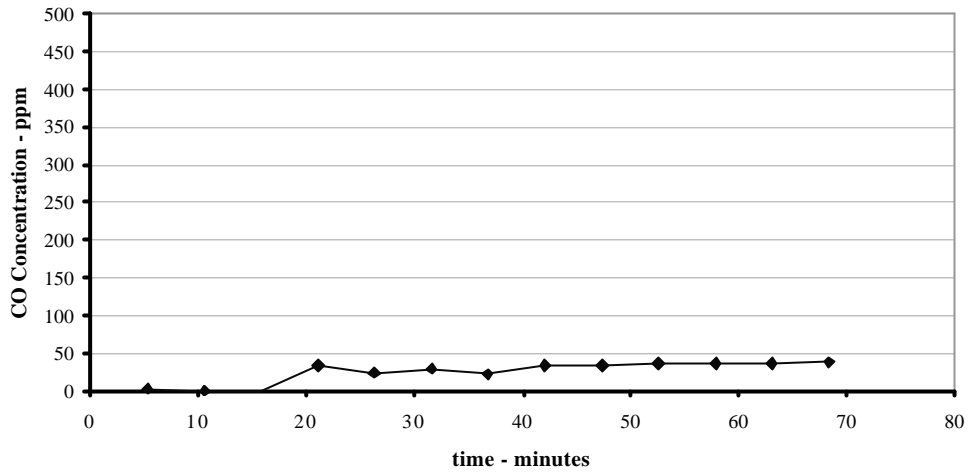


Figure A6(b)
Test 6. Concentration in the extract system

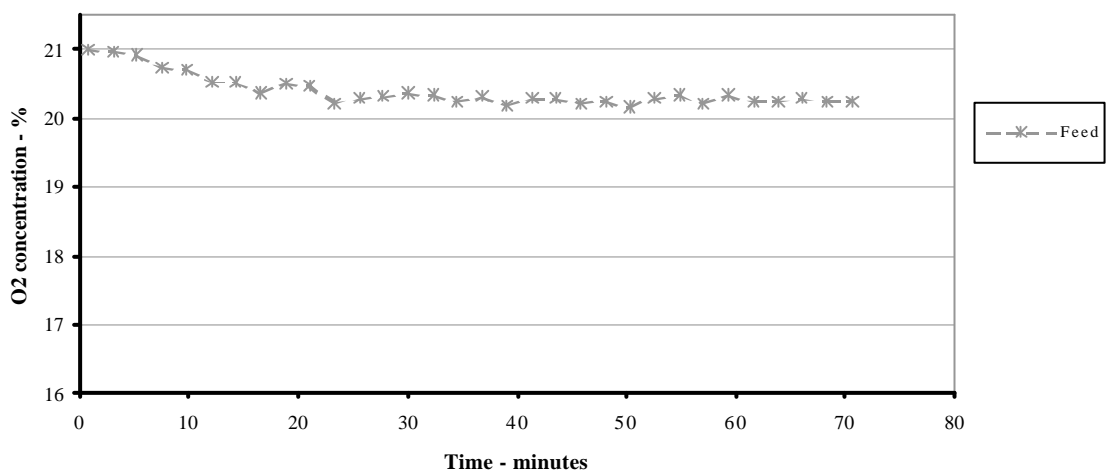
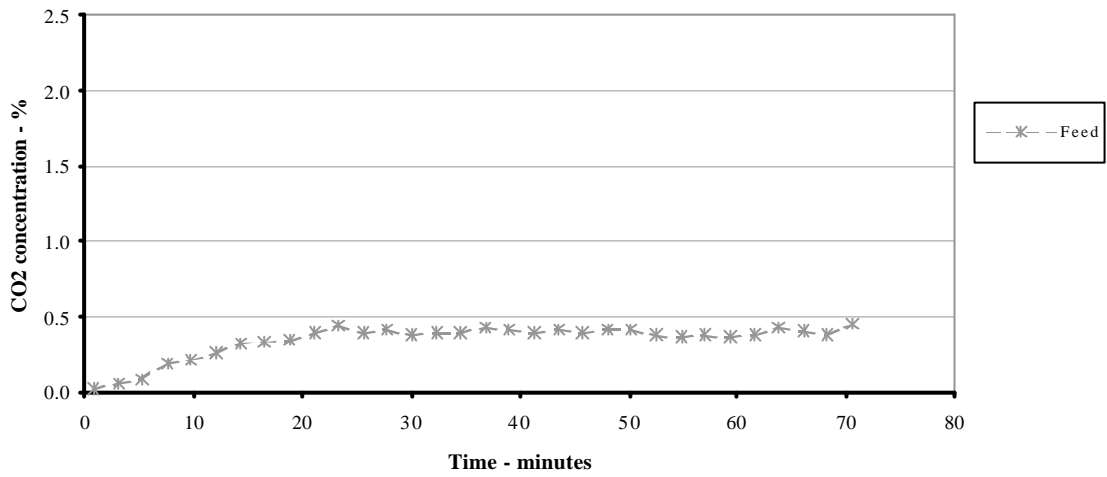
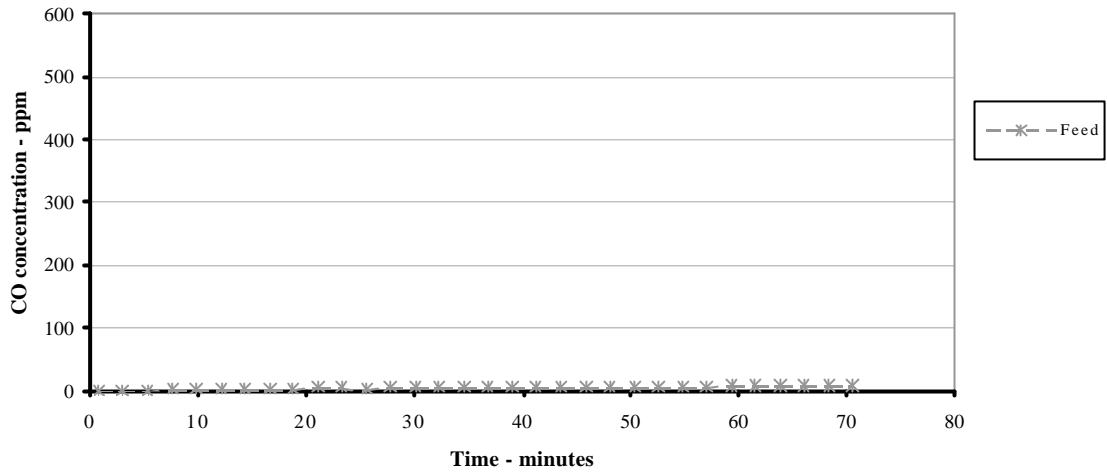


Figure A6(c)
Test 6. Concentration in the flue, and in the combustion air supply

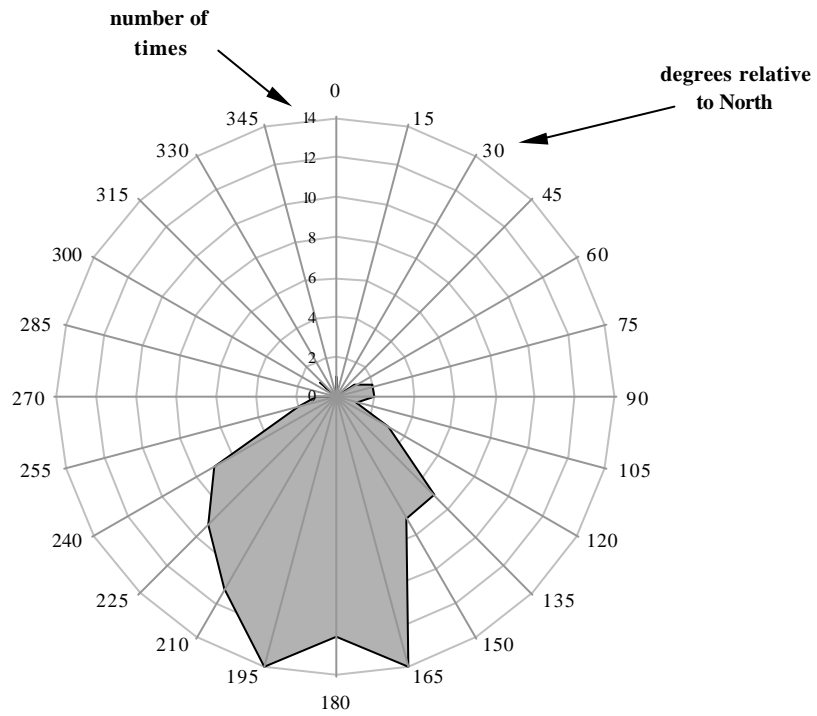
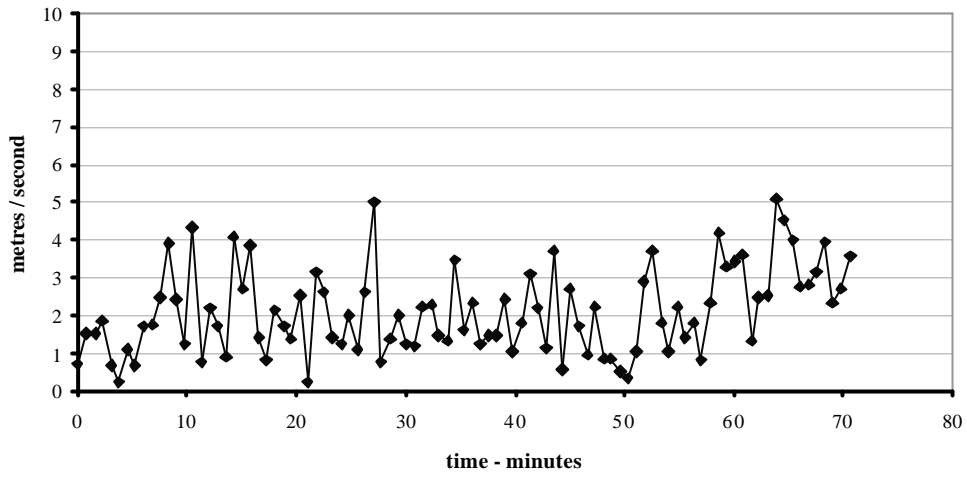


Figure A6(d)
Test 6. Wind speed and direction

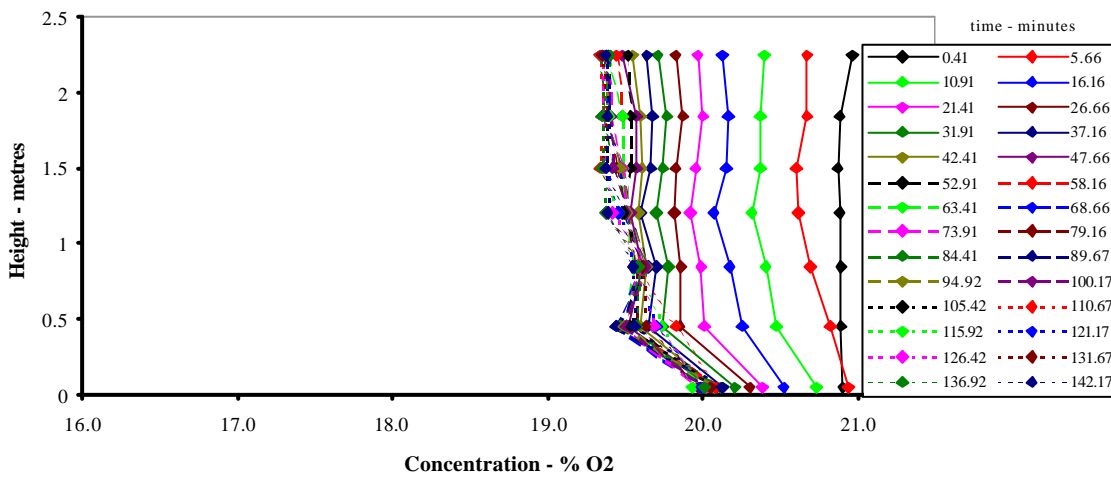
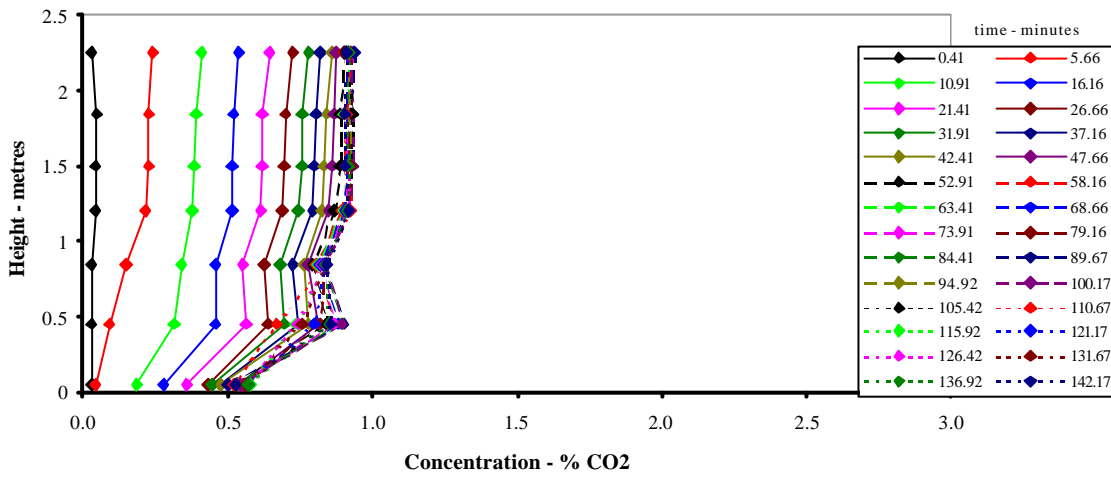
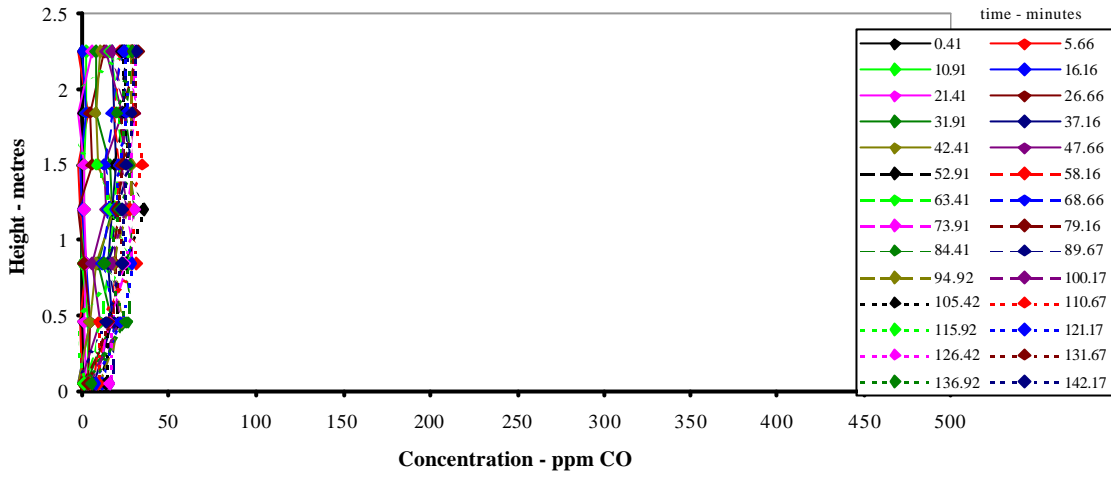


Figure A7(a)
Test 7. Concentration profiles in Room 1

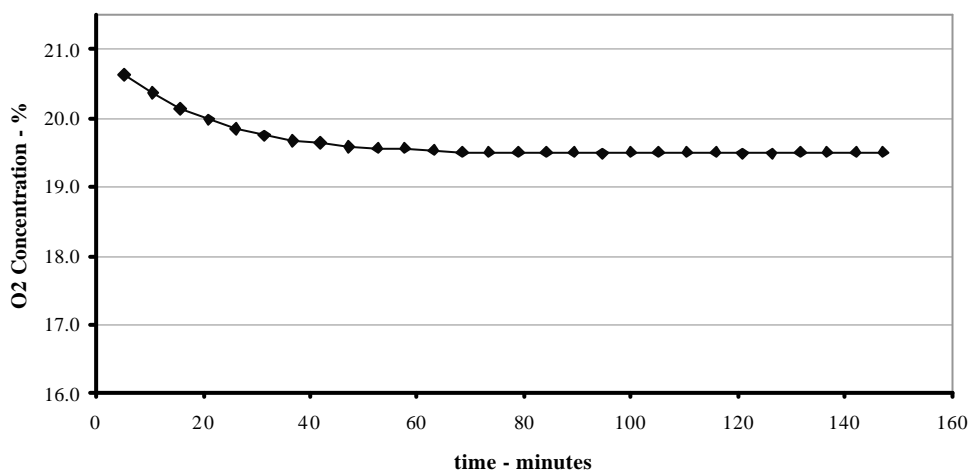
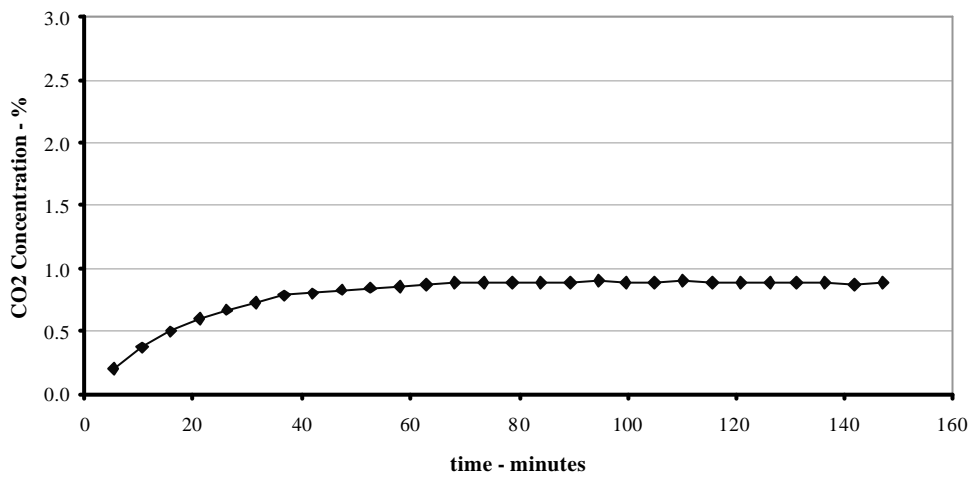
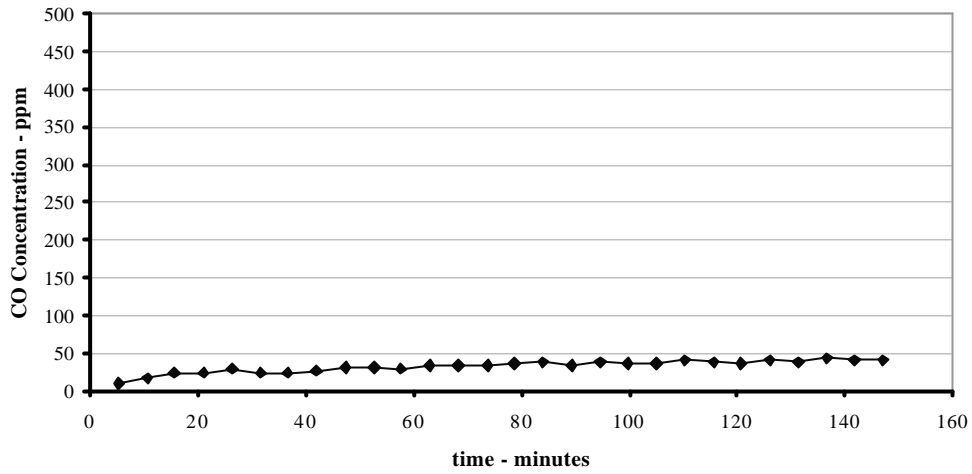


Figure A7(b)
Test 7. Concentration in the extract system

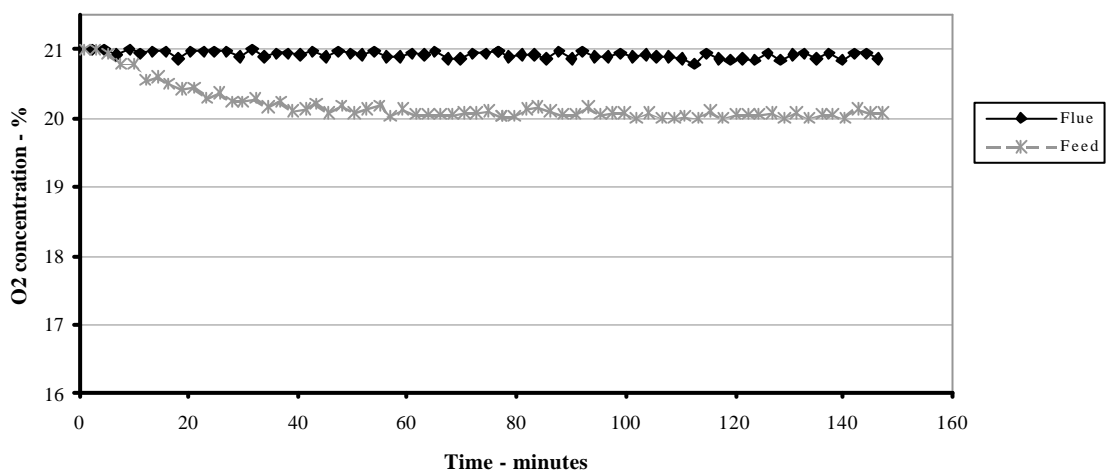
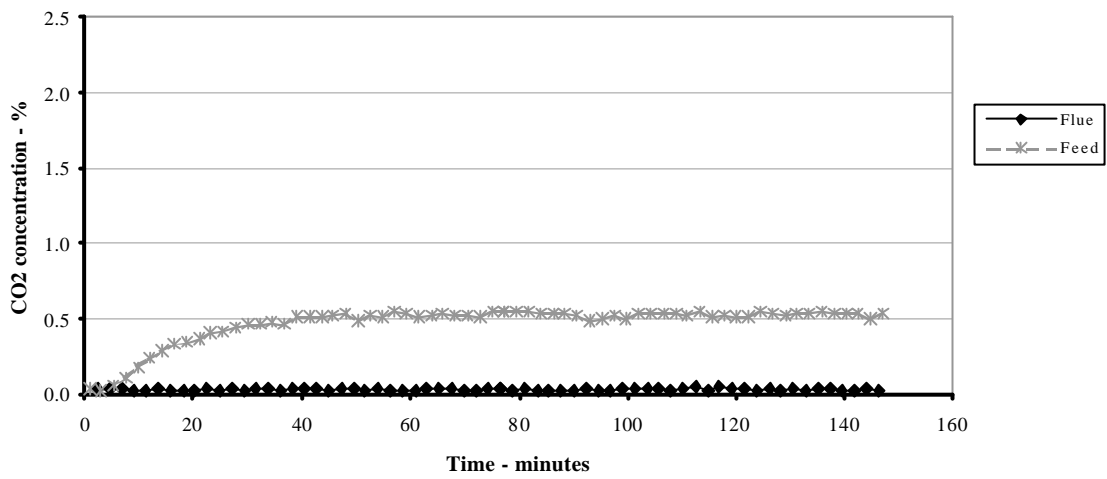
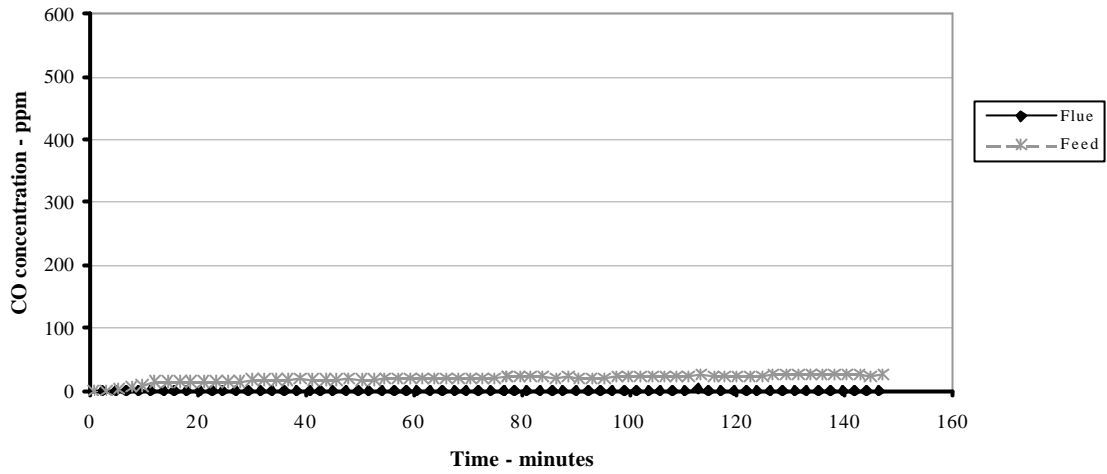


Figure A7(c)
Test 7. Concentration in the flue, and in the combustion air supply

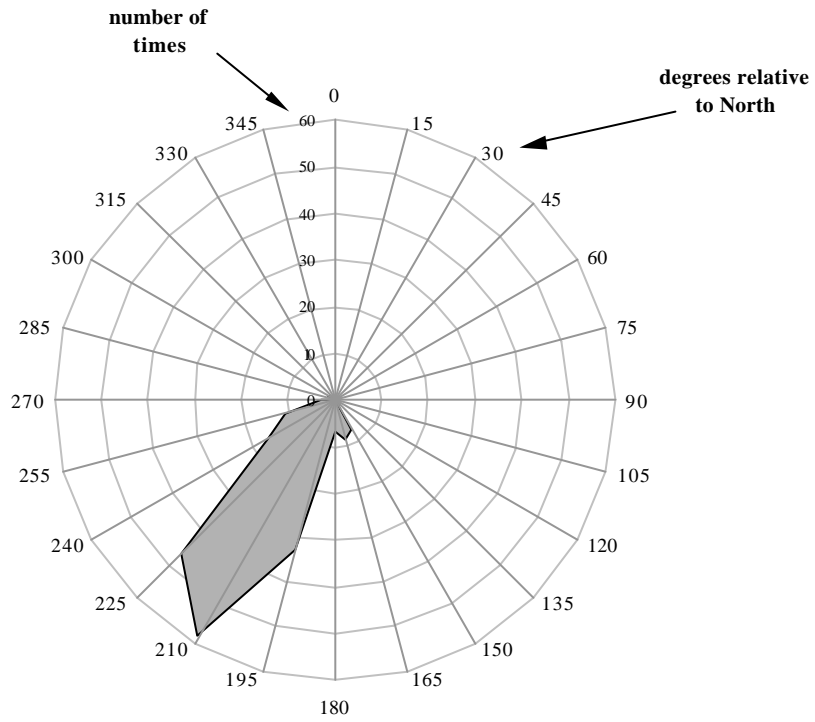
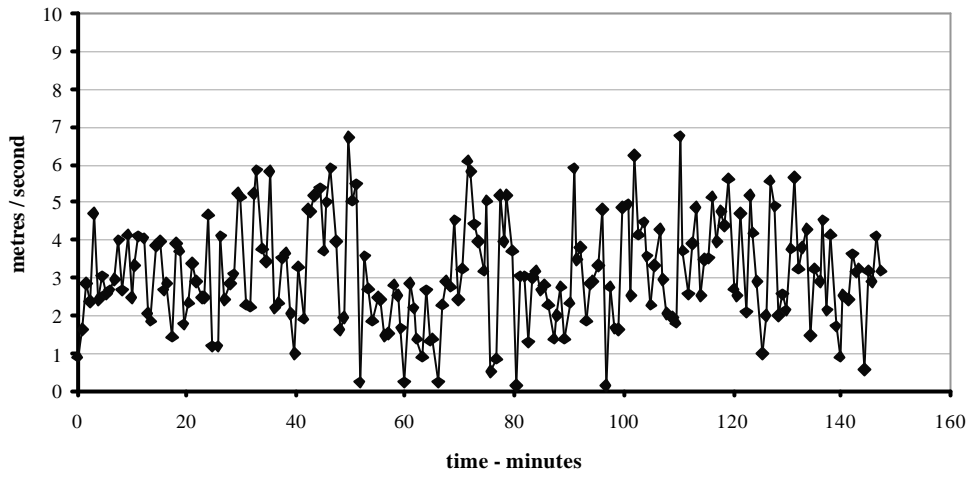


Figure A7(d)
Test 7. Wind speed and direction

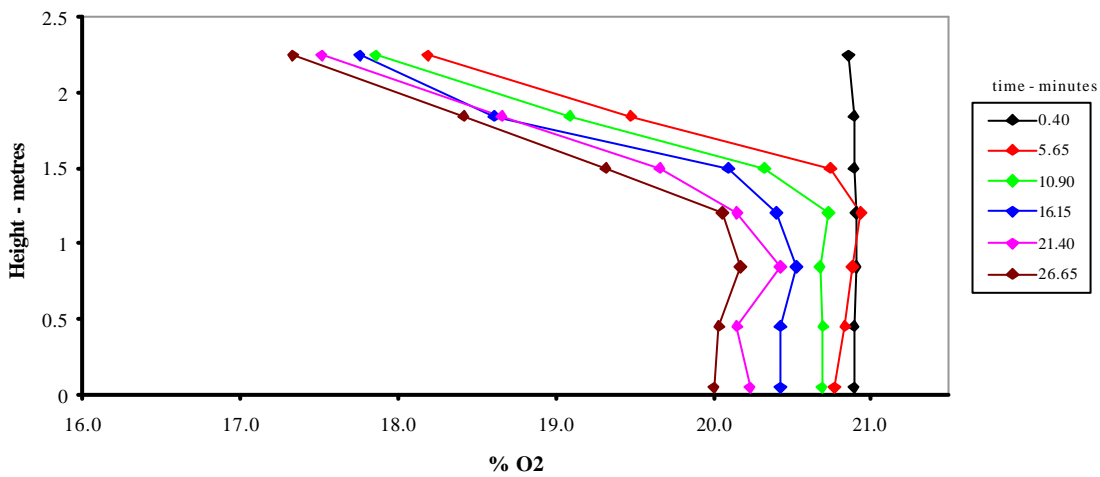
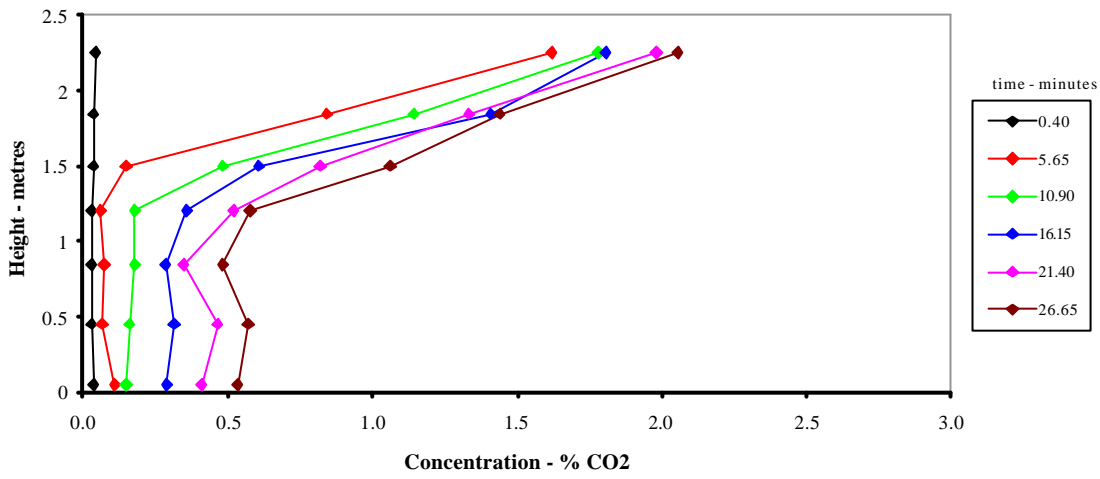
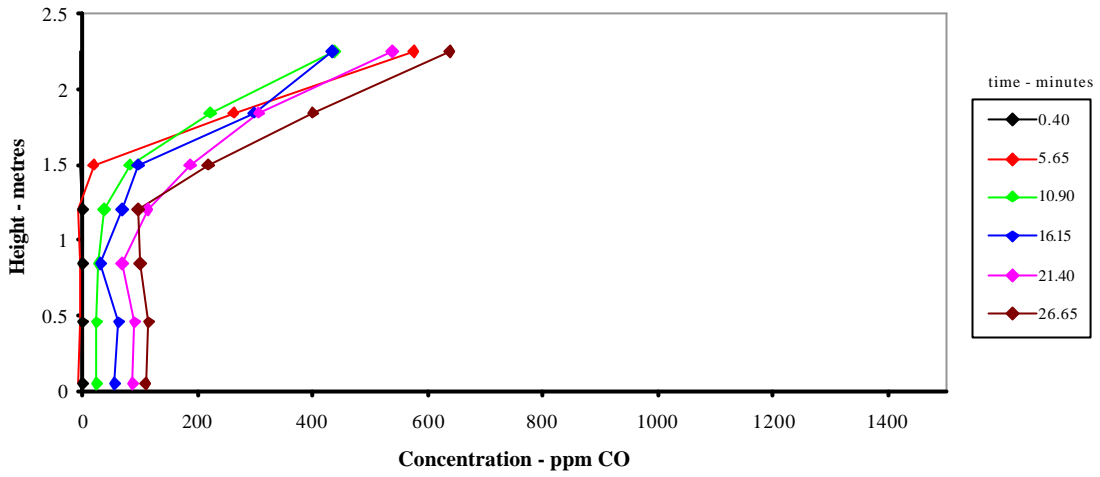


Figure A8(a)
Test 8. Concentration profiles in Room 1

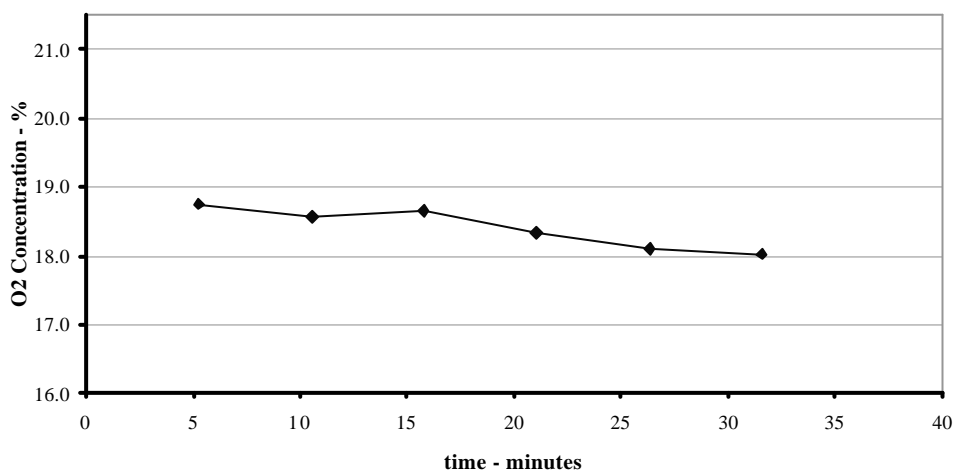
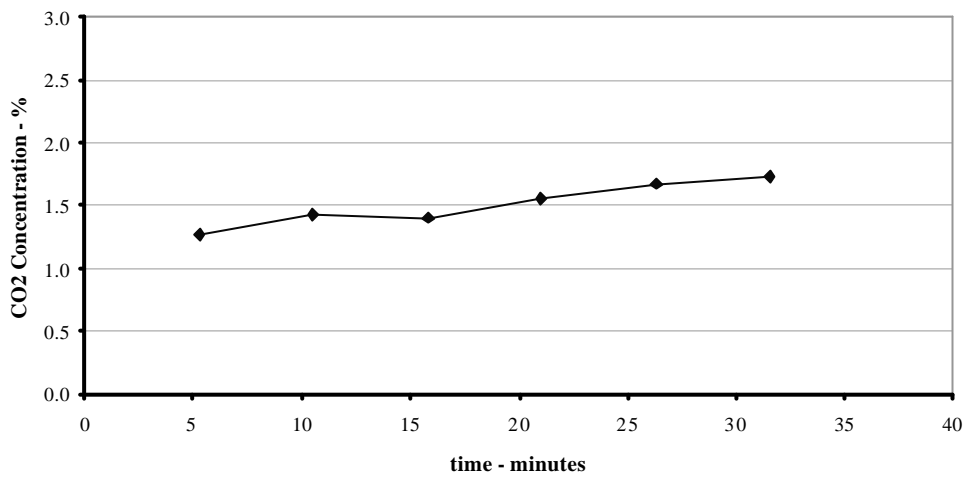
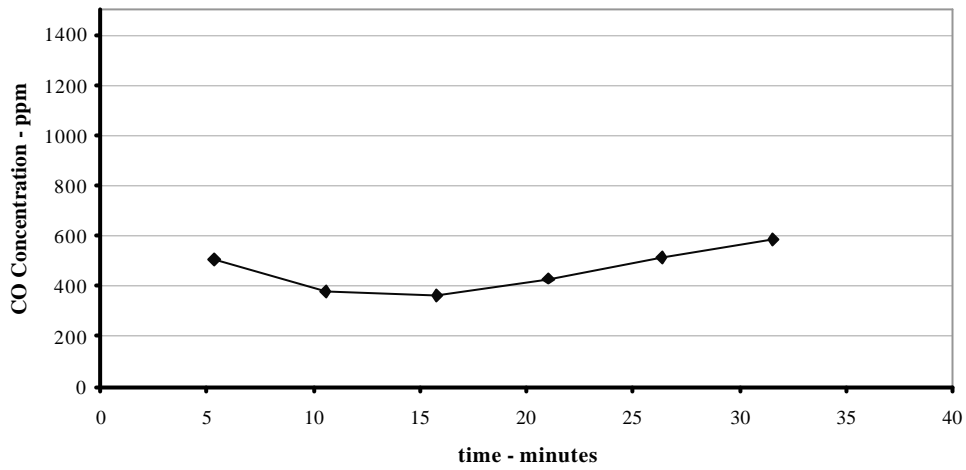


Figure A8(b)
Test 8. Concentration in the extract system

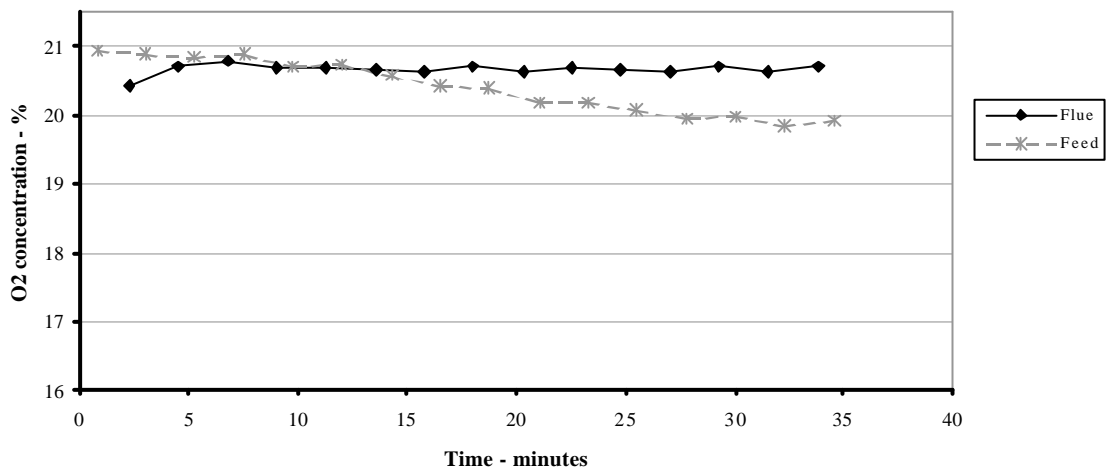
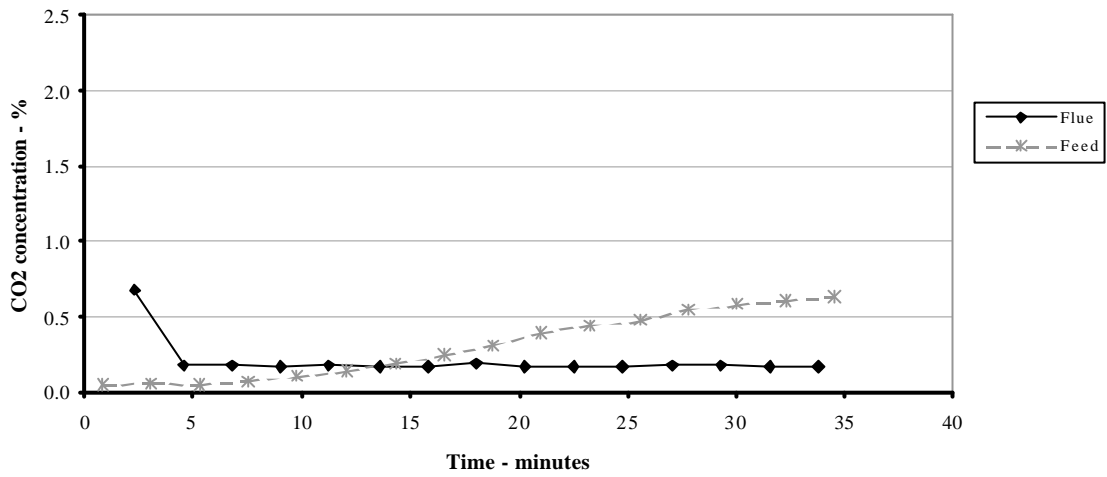
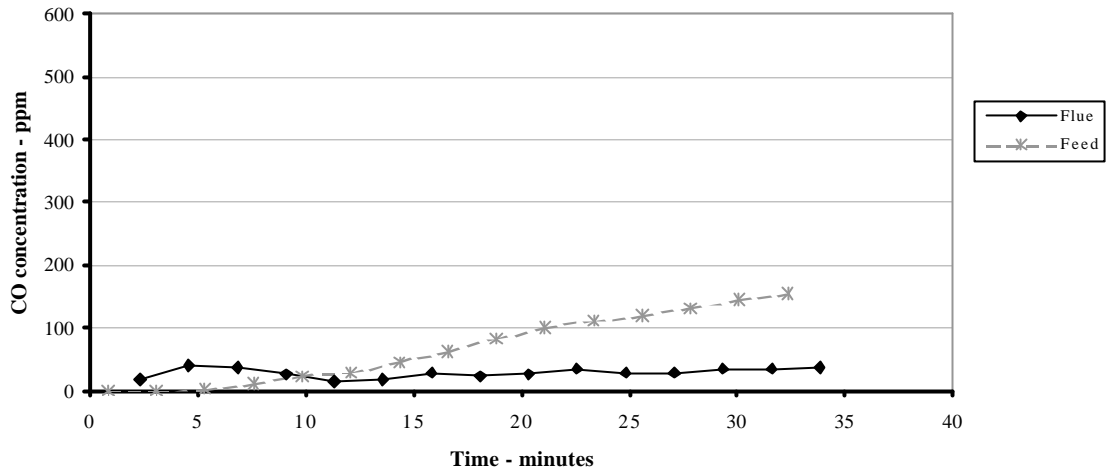


Figure A8(c)
Test 8. Concentration in the flue, and in the combustion air supply

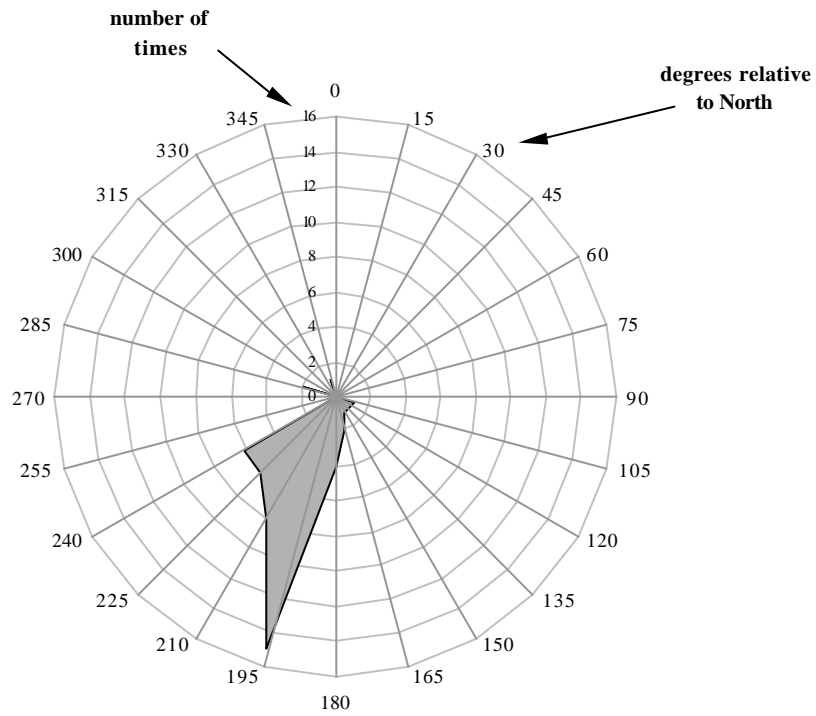
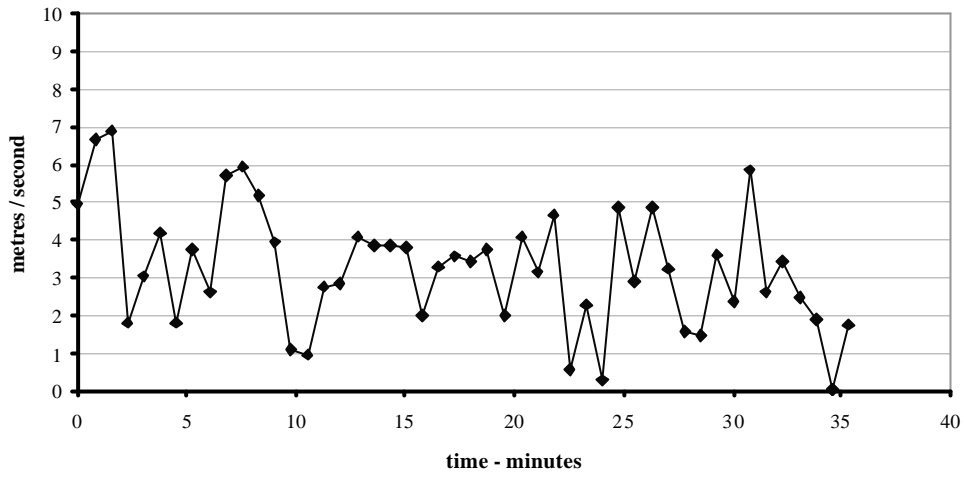


Figure A8(d)
Test 8. Wind speed and direction

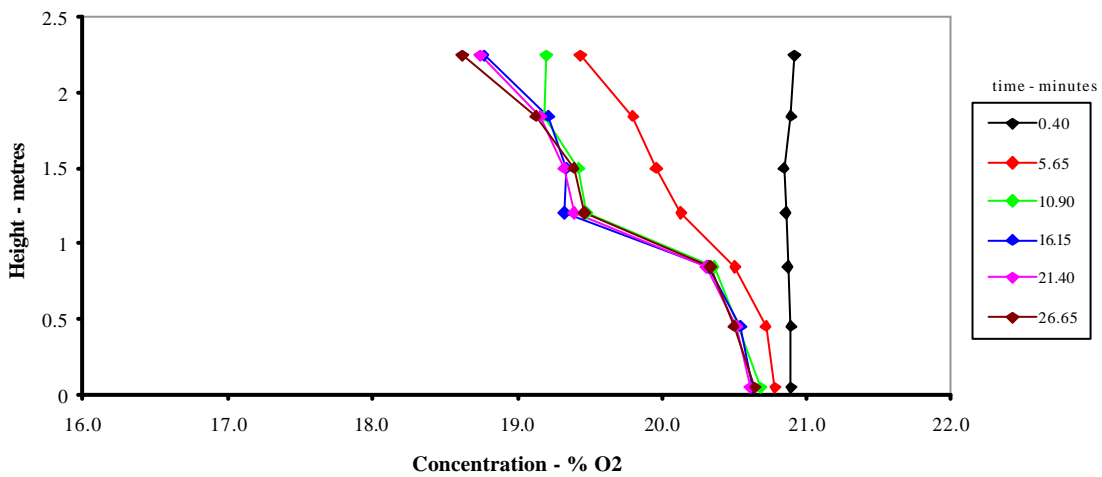
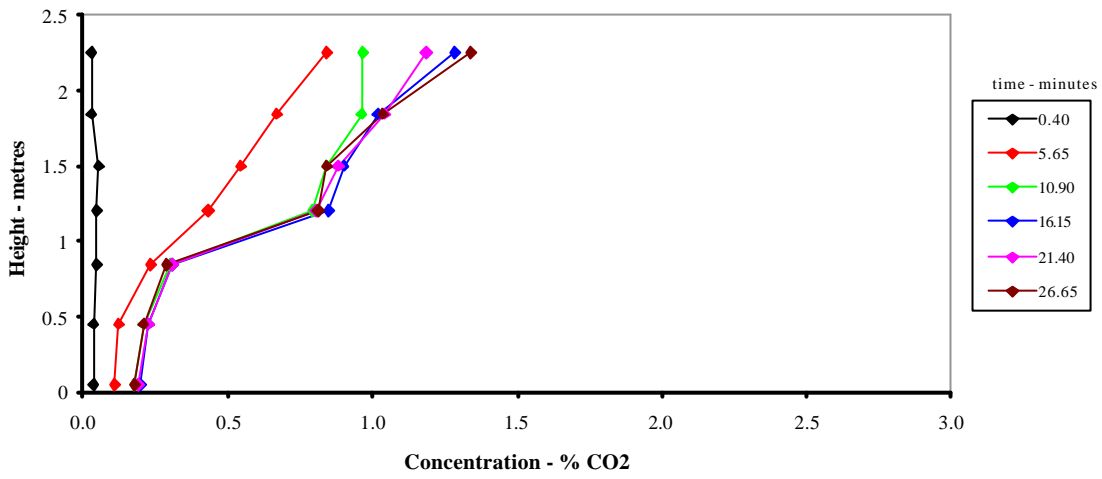
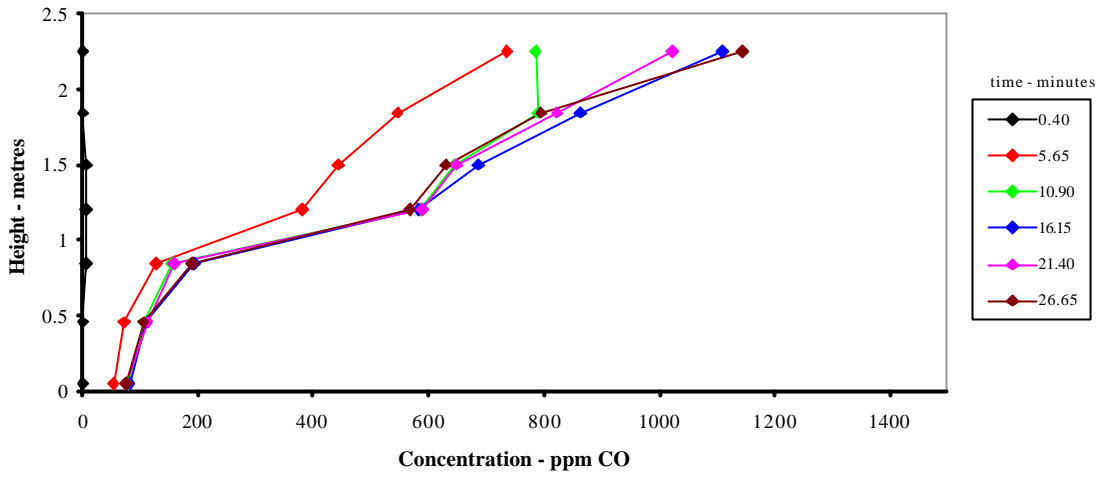


Figure A9(a)
Test 9. Concentration profiles in Room 1

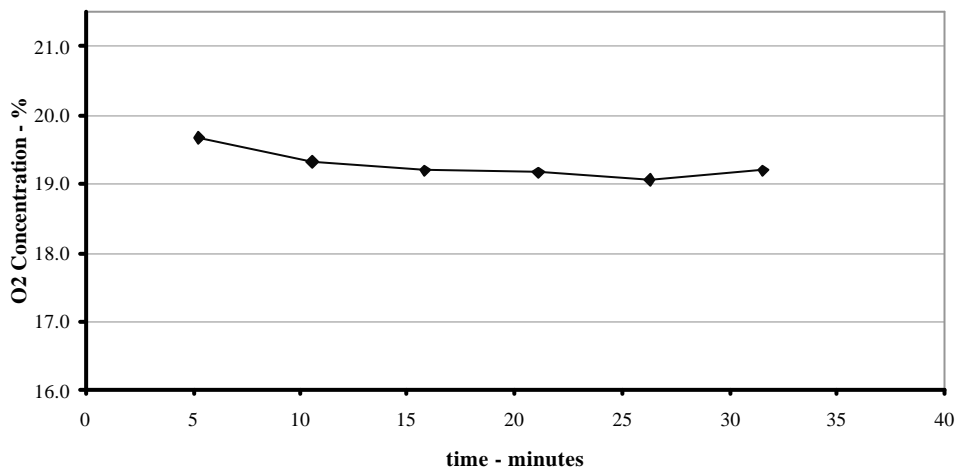
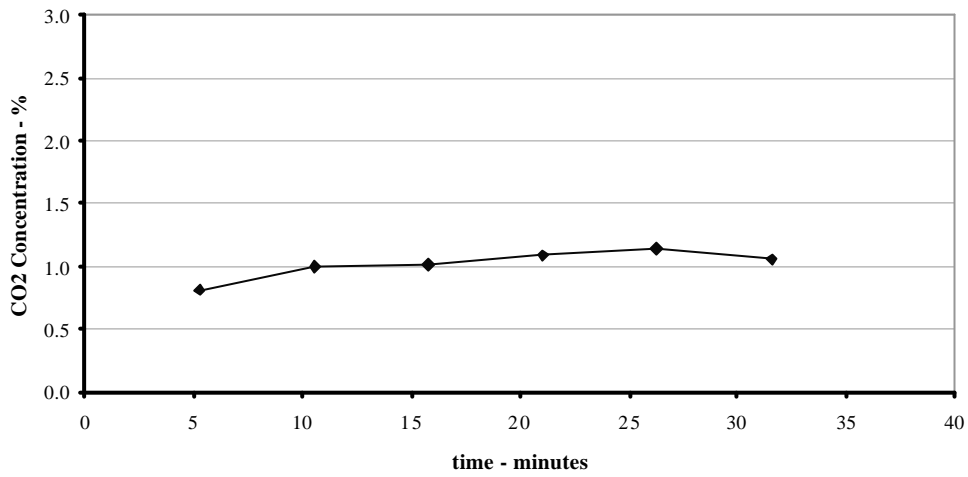
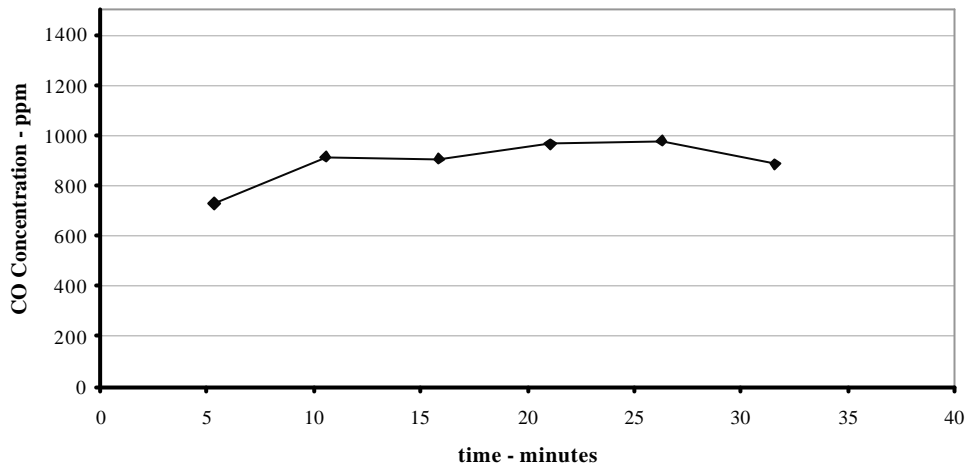


Figure A9(b)
Test 9. Concentration in the extract system

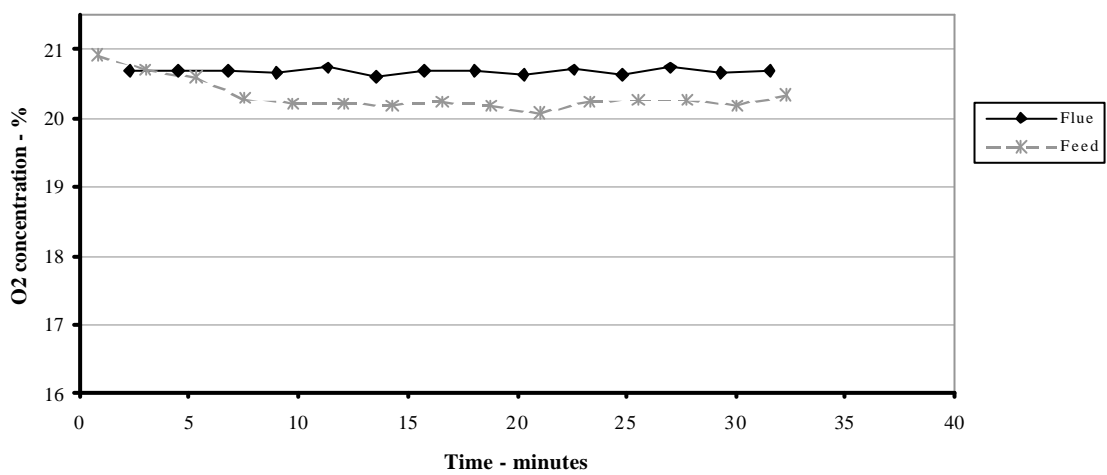
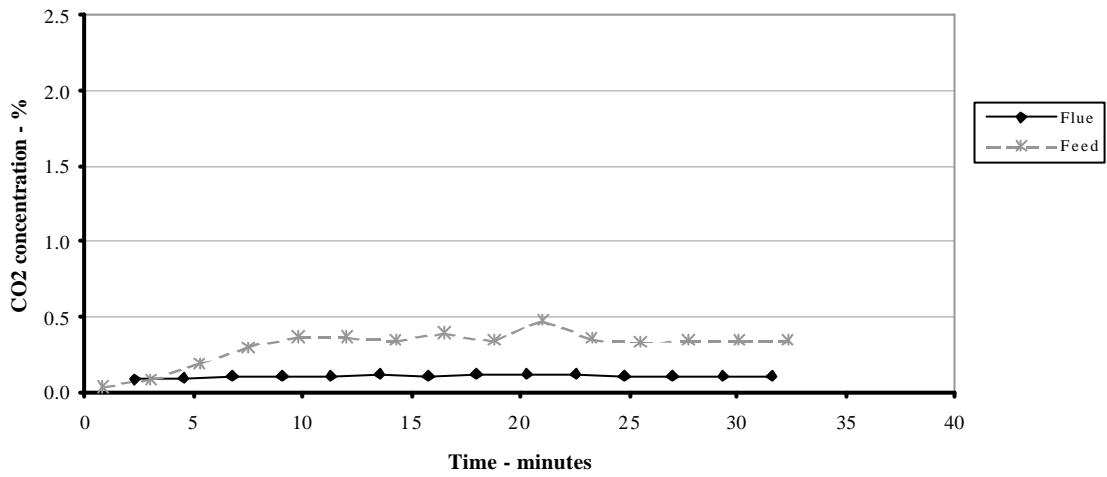
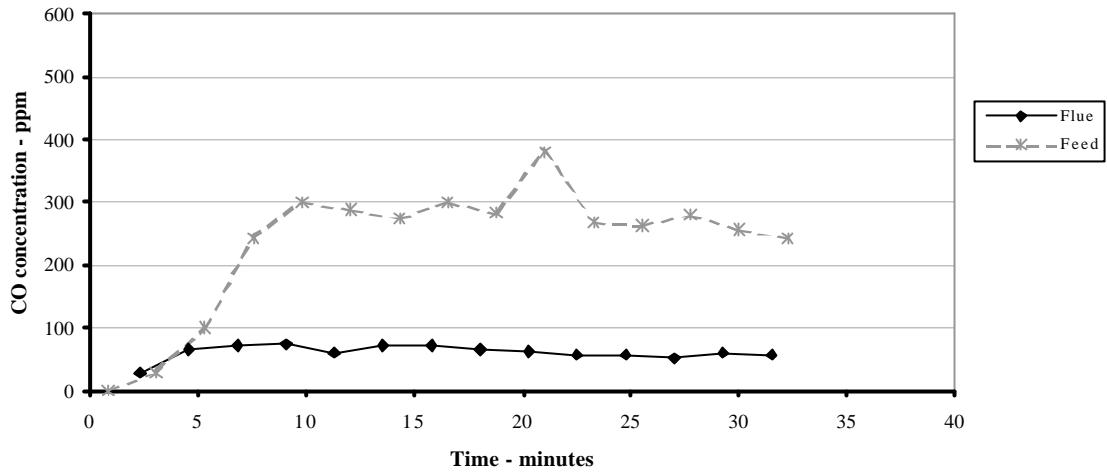


Figure A9(c)
Test 9. Concentration in the flue, and in the combustion air supply

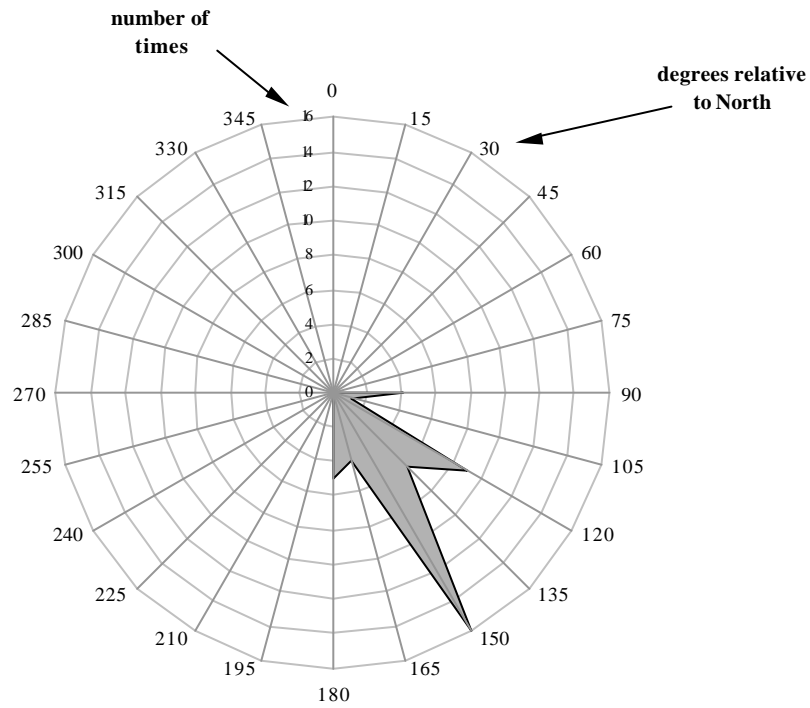
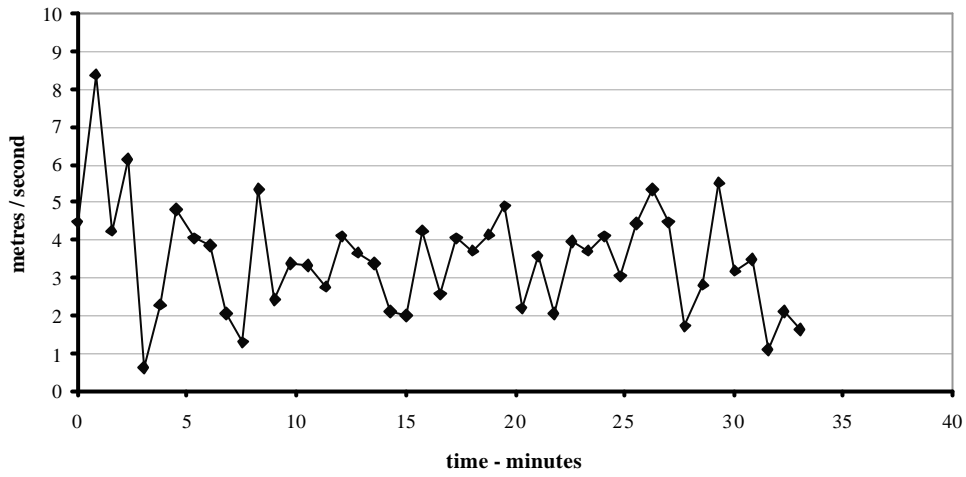


Figure A9(d)
Test 9. Wind speed and direction

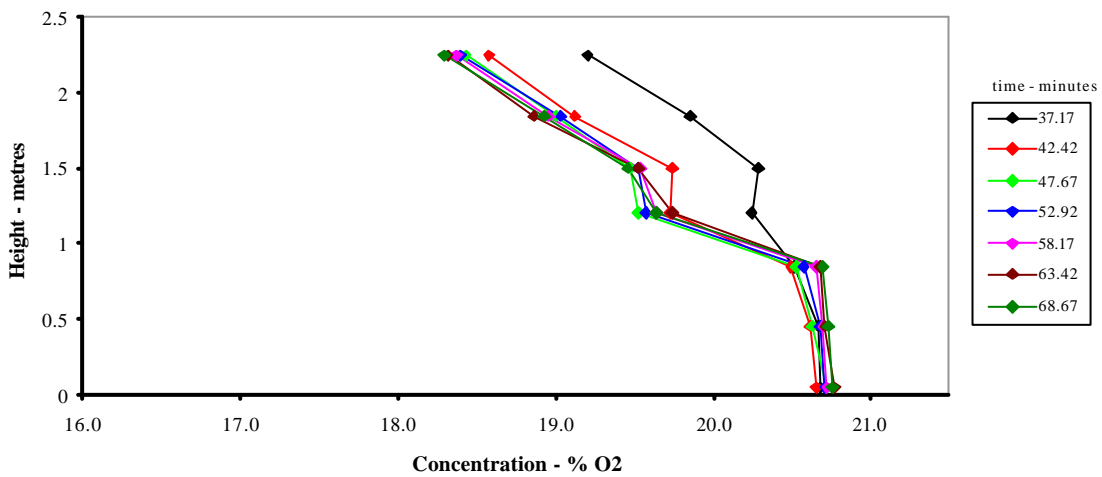
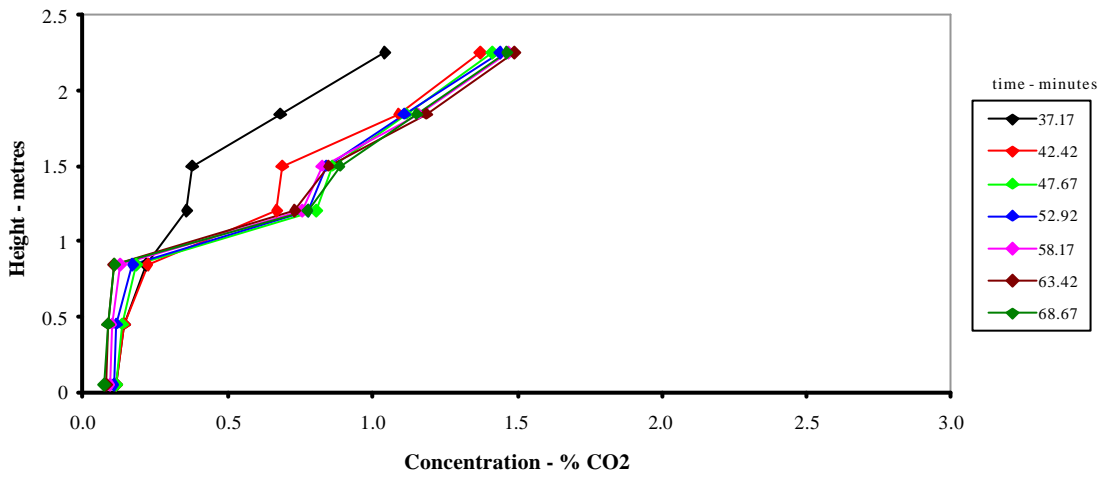
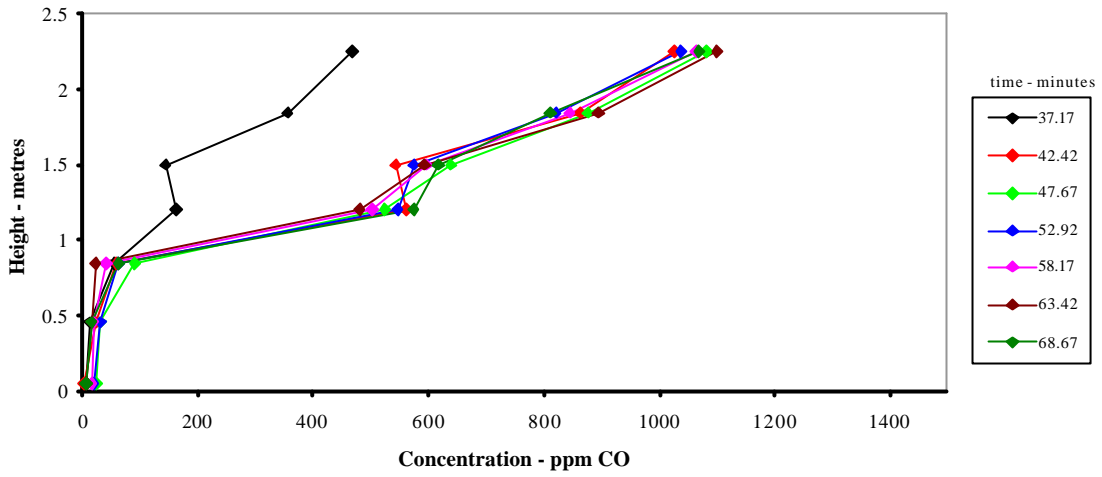


Figure A10(a)
Test 10. Concentration profiles in Room 1

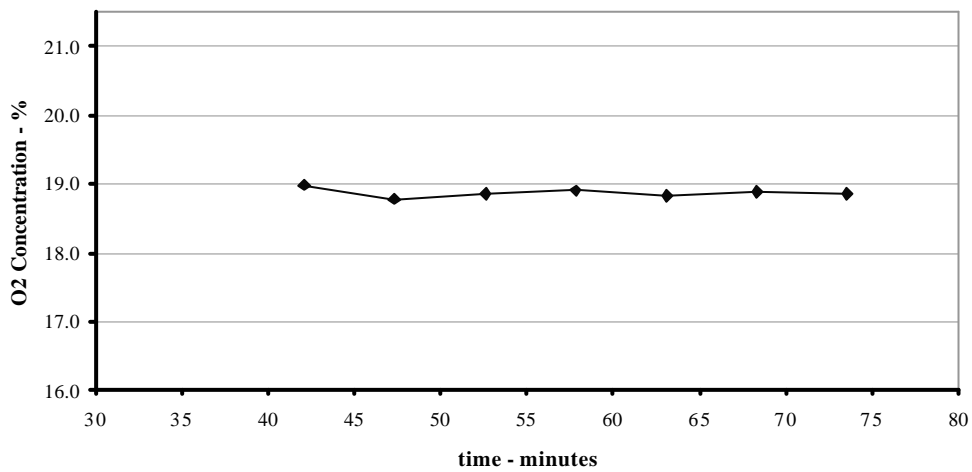
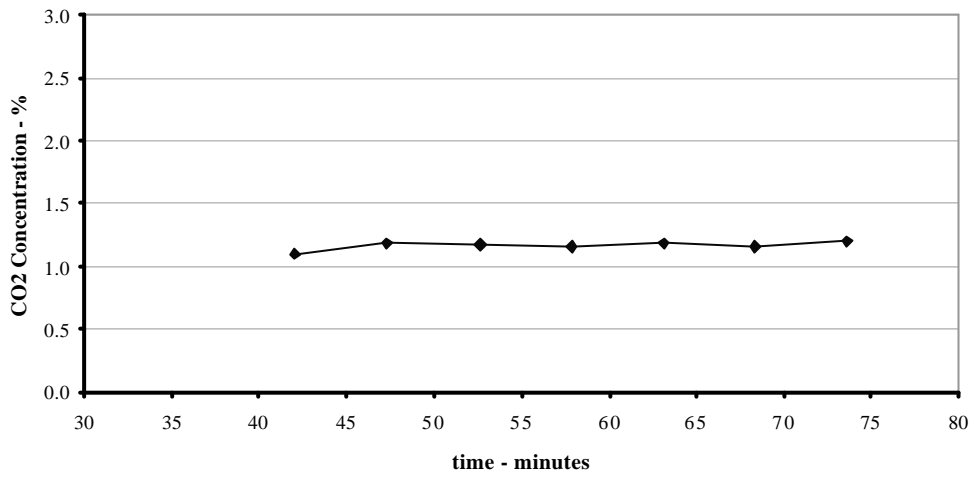
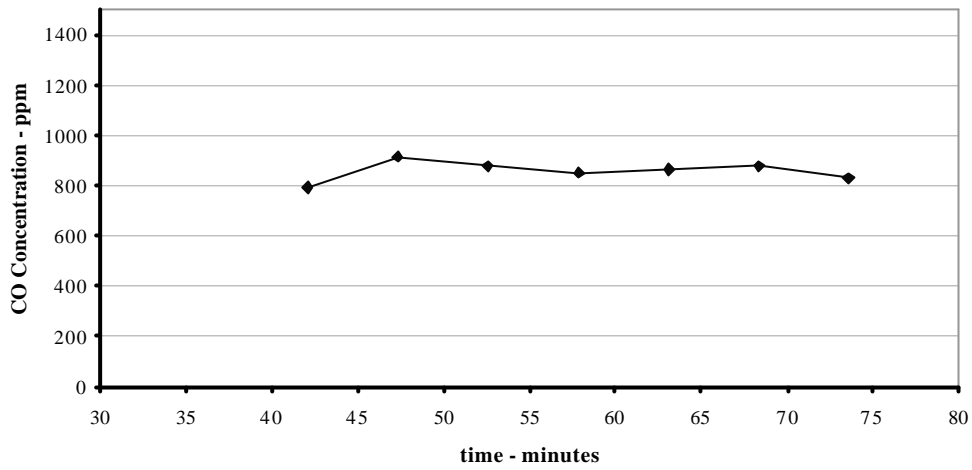


Figure A10(b)
Test 10. Concentration in the extract system

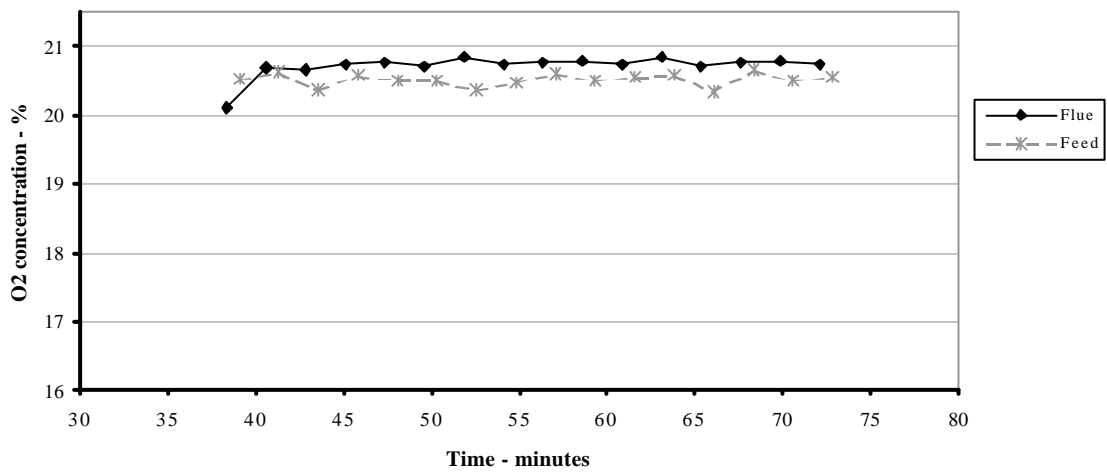
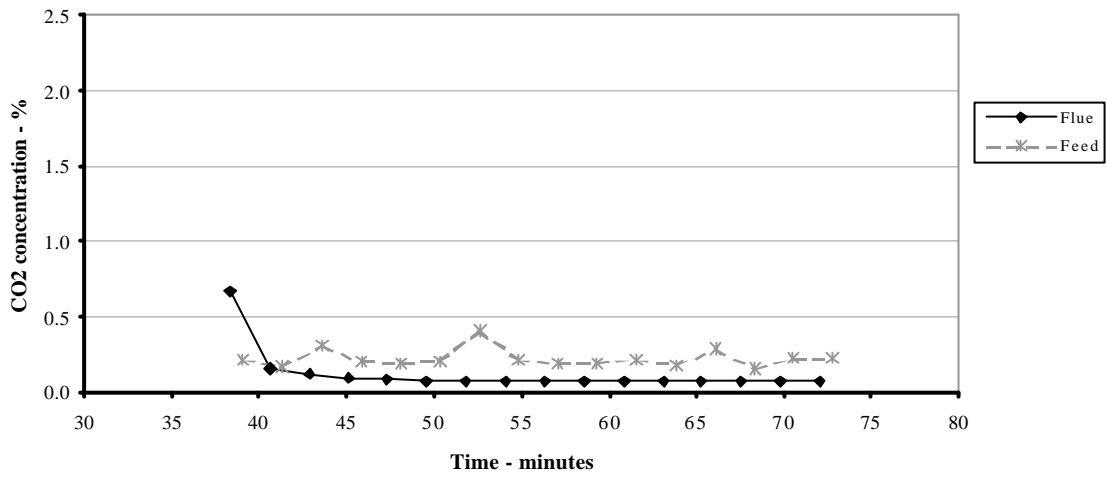
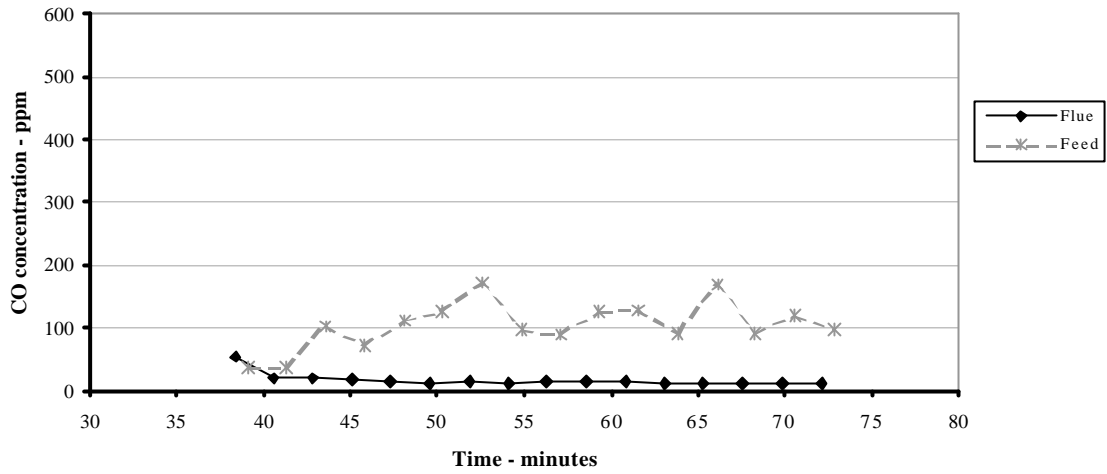


Figure A10(c)
Test 10. Concentration in the flue, and in the combustion air supply

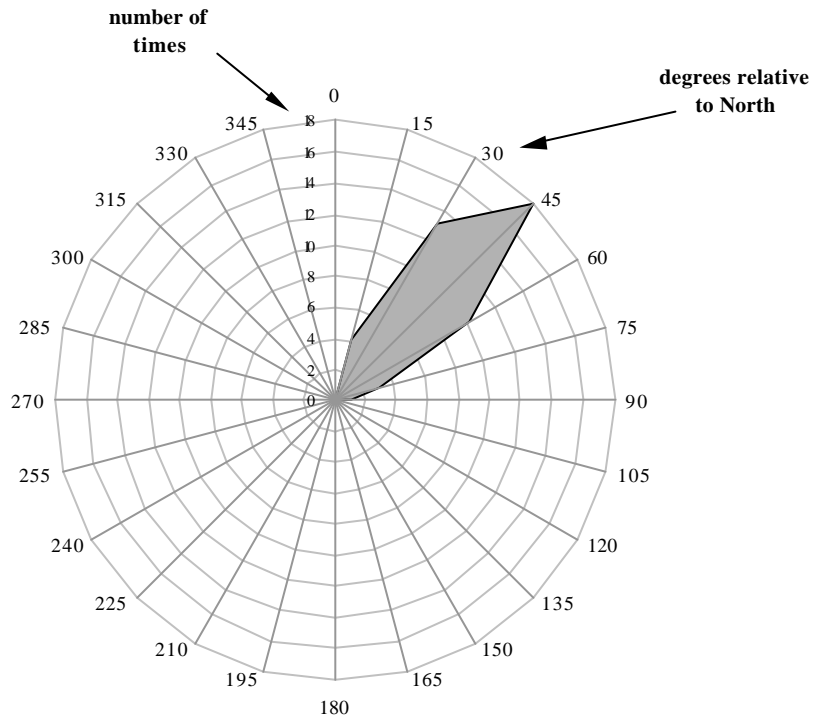
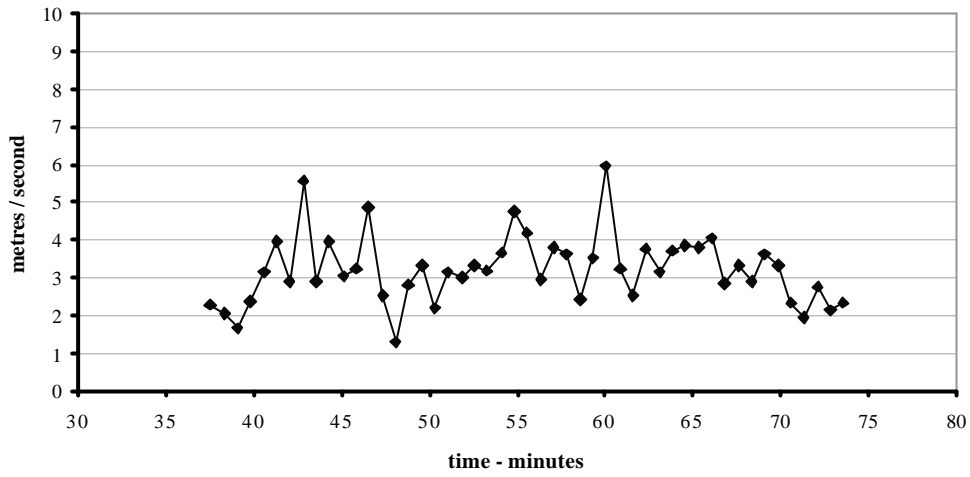


Figure A10(d)
Test 10. Wind speed and direction

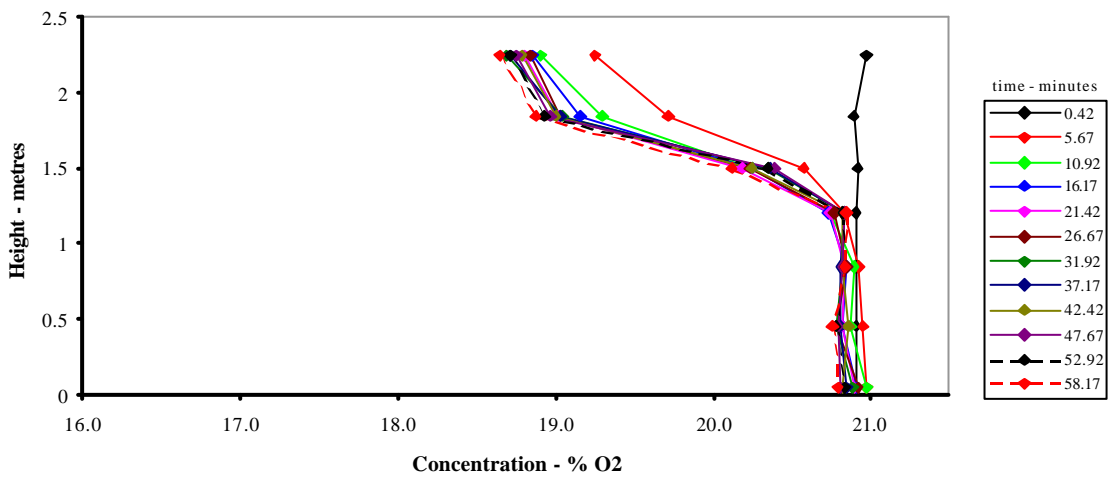
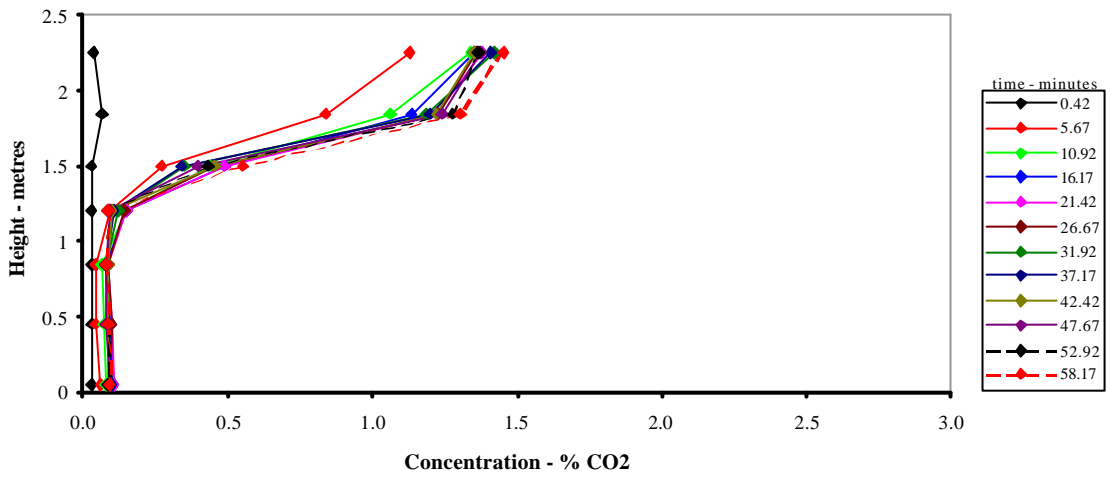
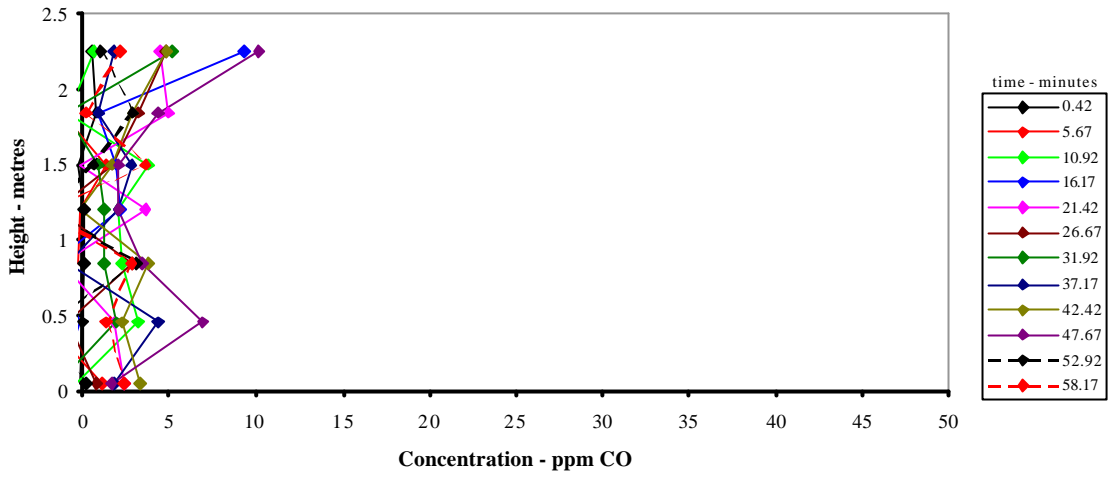


Figure A11(a)
Test 11, Concentration profiles in Room 1

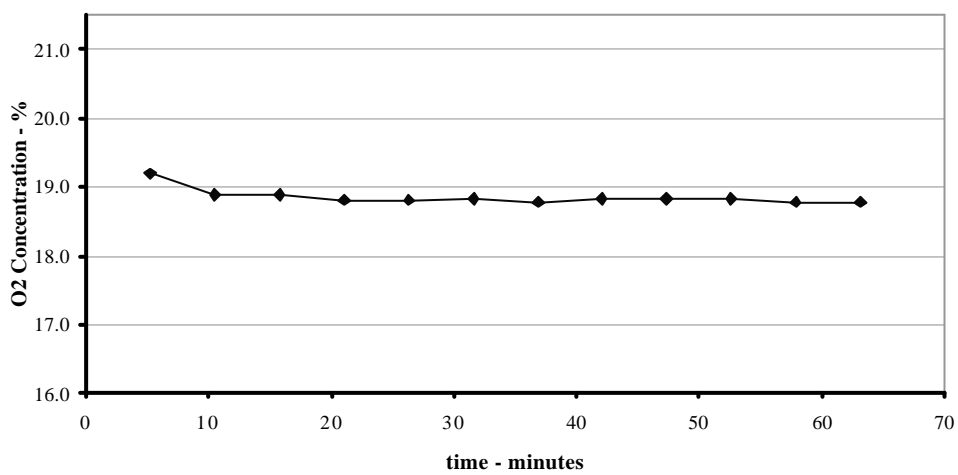
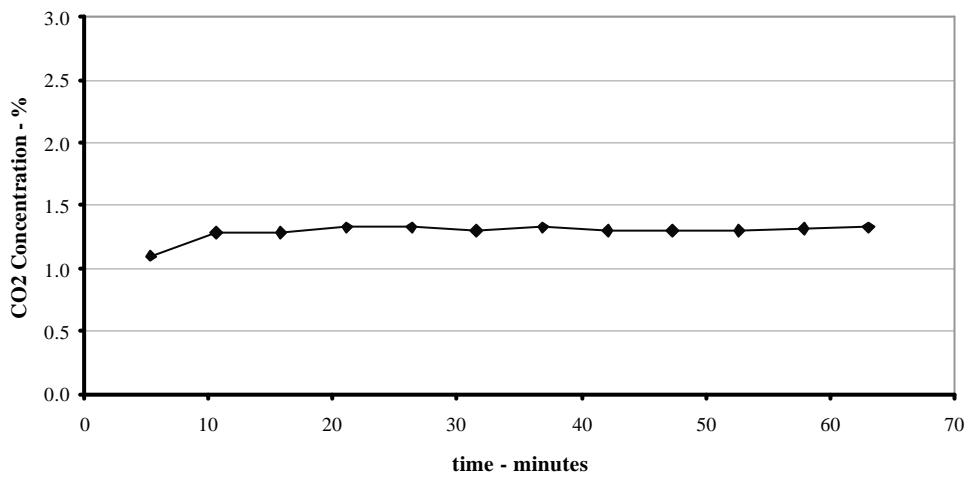
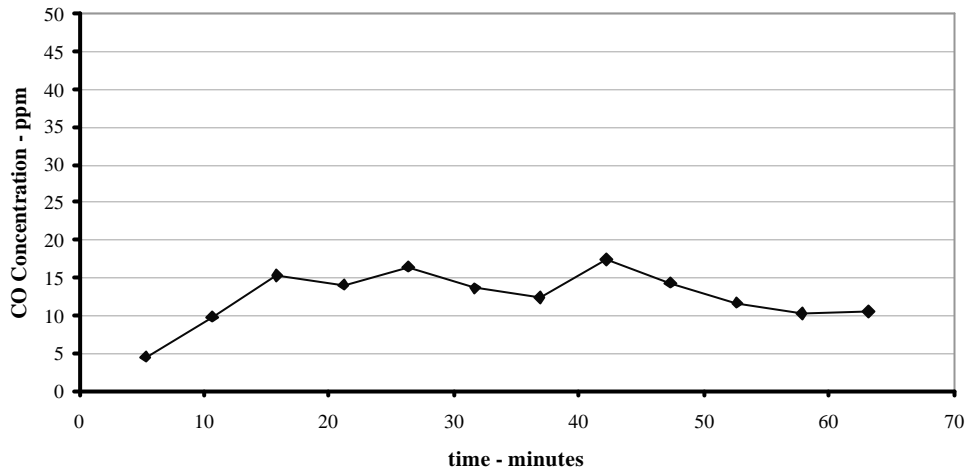


Figure A11(b)
Test 11. Concentration in the extract system

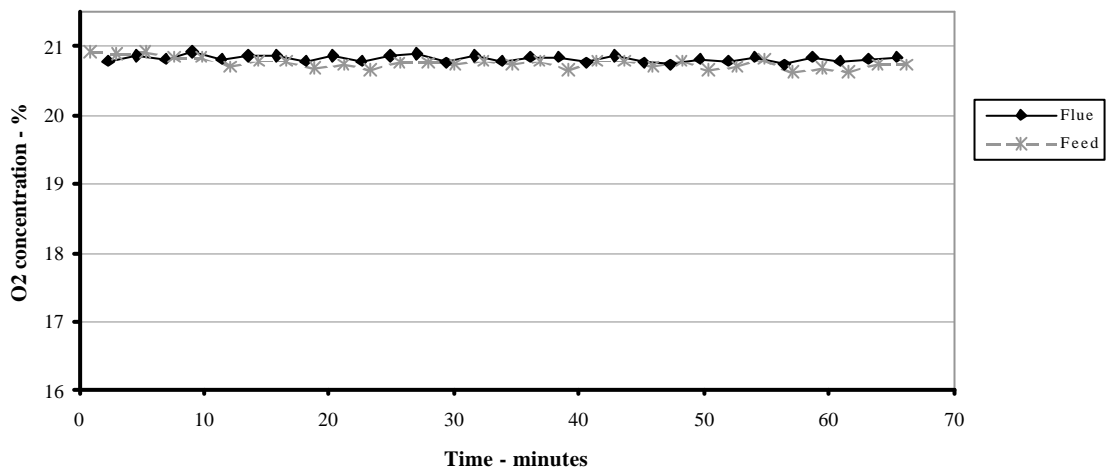
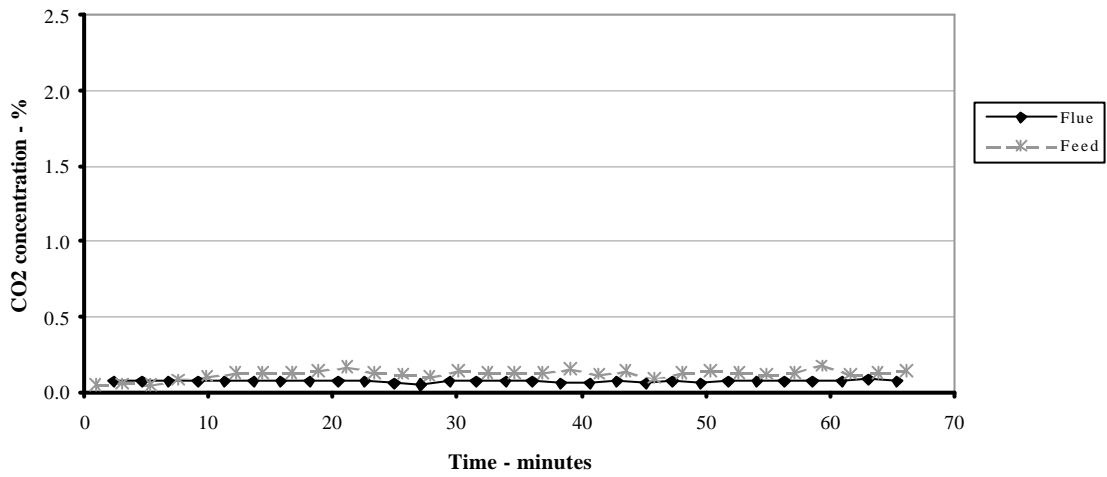
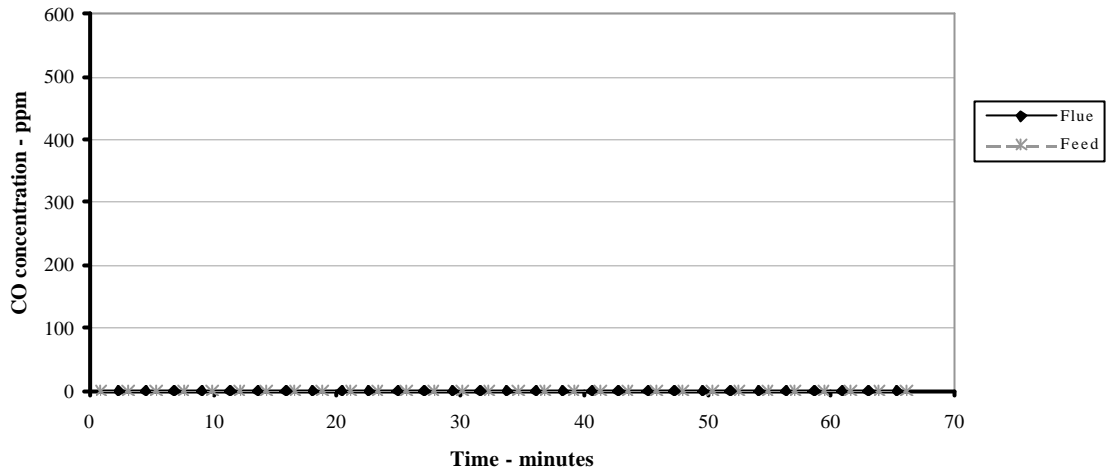


Figure A11(c)
Test 11. Concentration in the flue, and in the combustion air supply

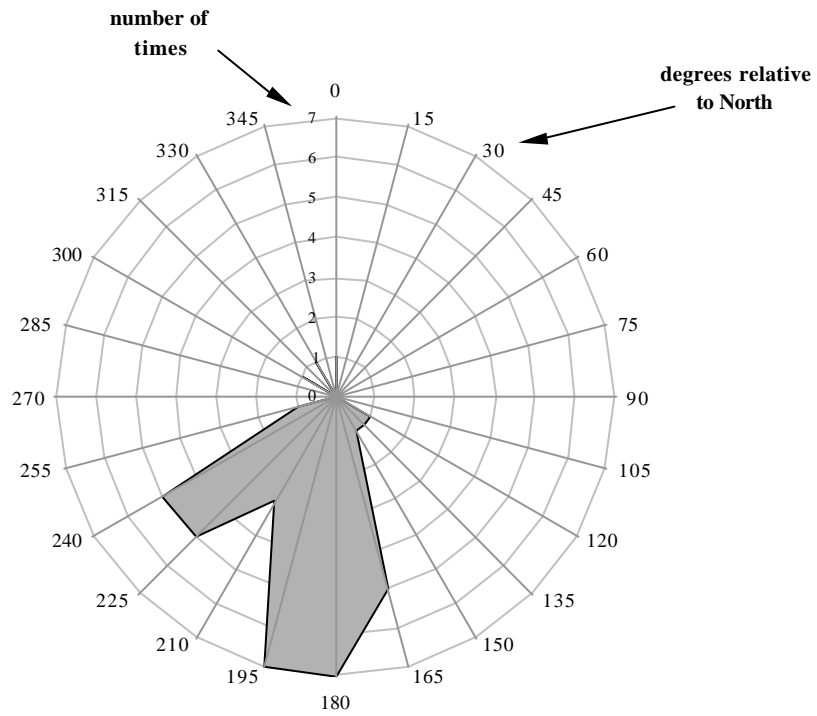
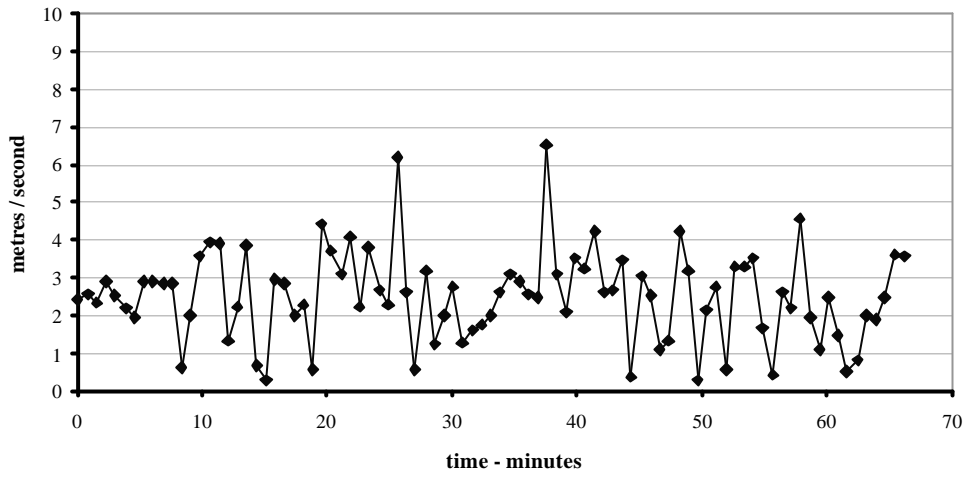


Figure A11(d)
Test 11. Wind speed and direction

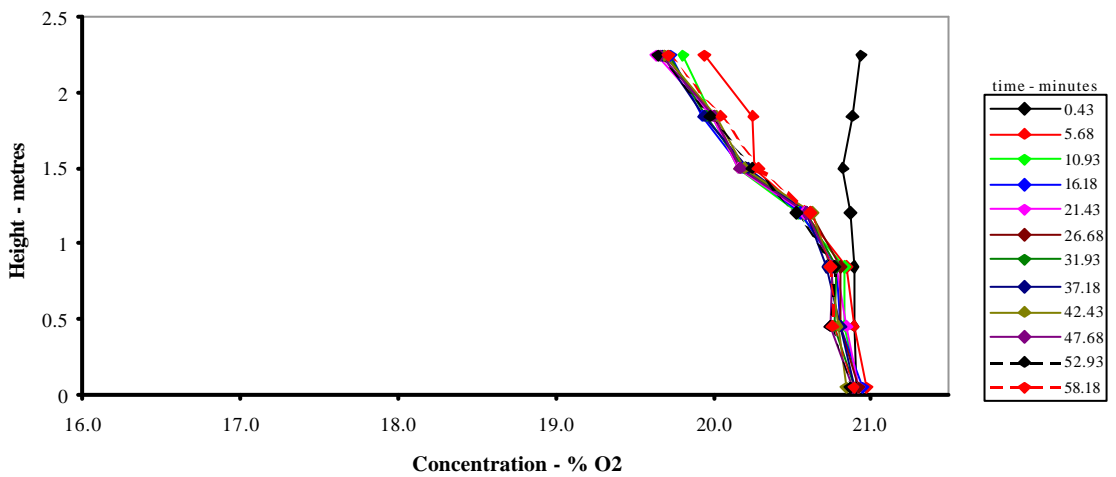
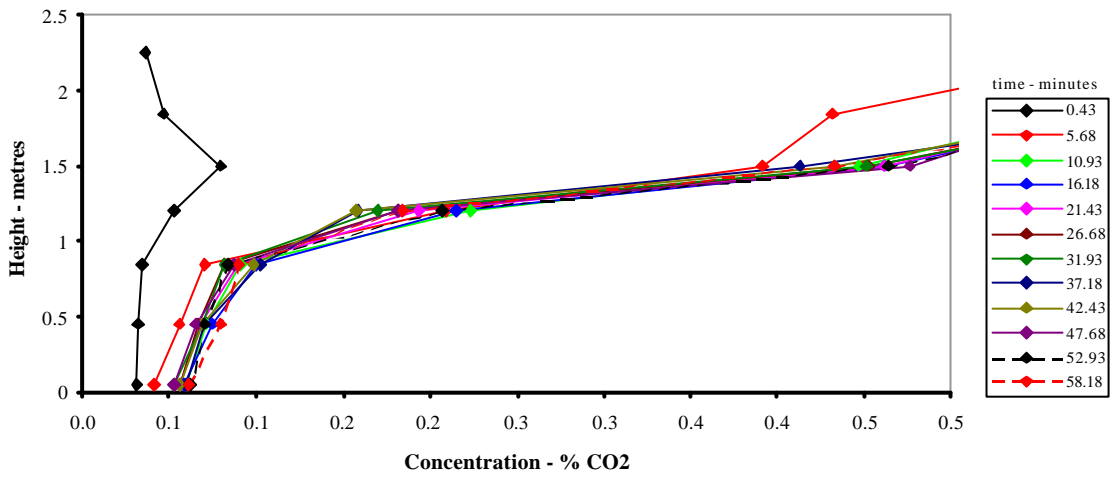
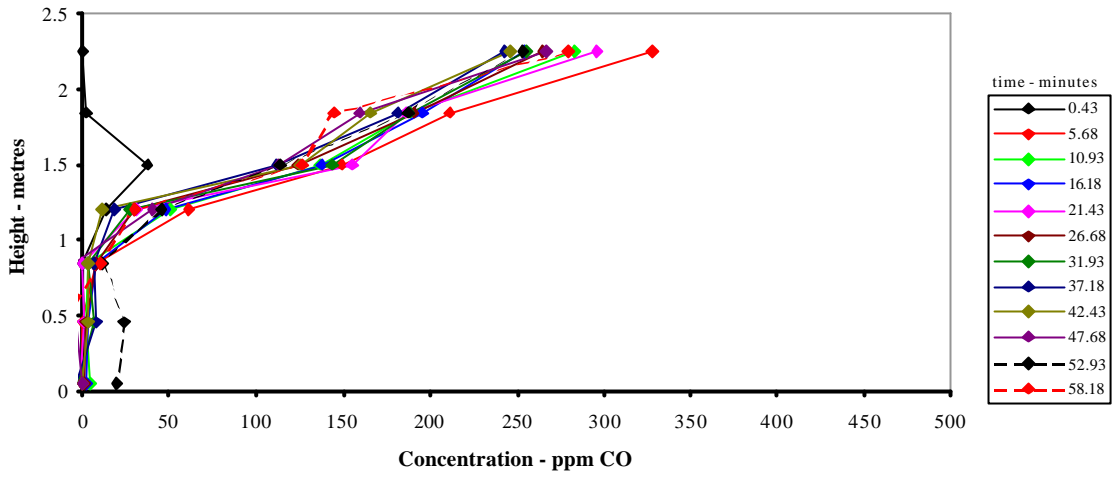


Figure A12(a)
Test 12. Concentration profiles in Room 1

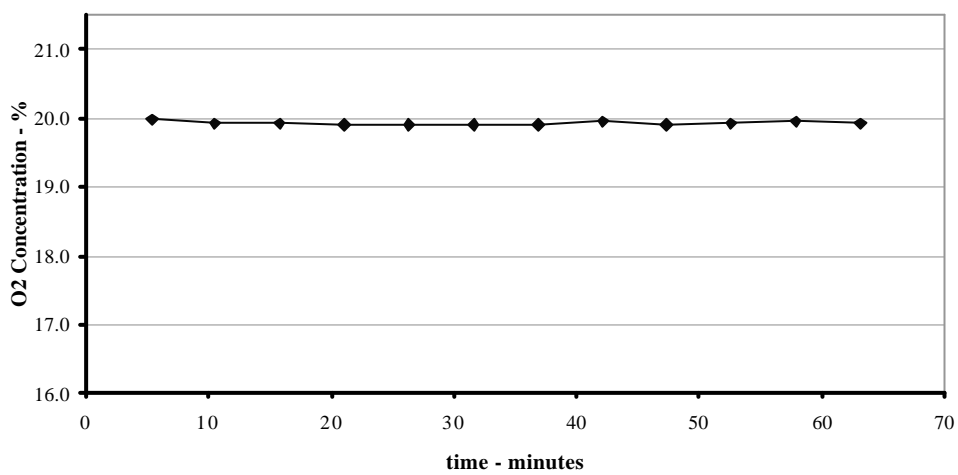
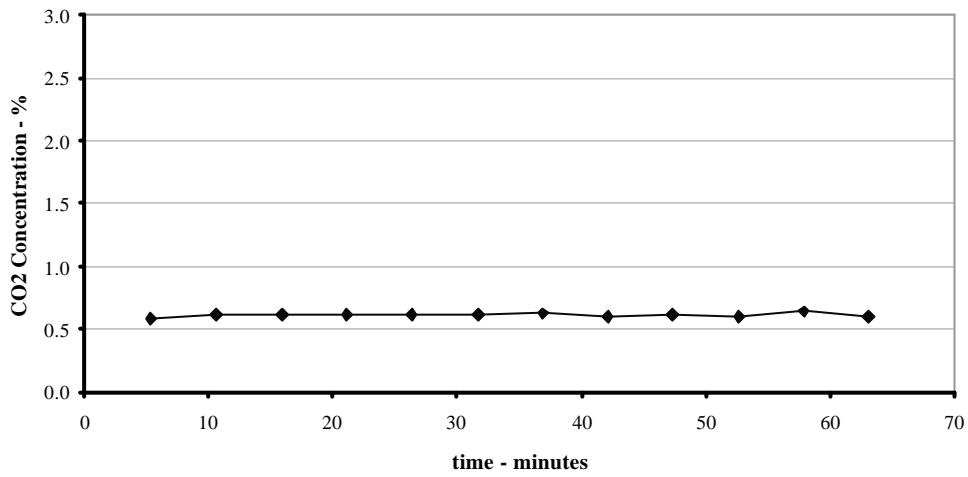
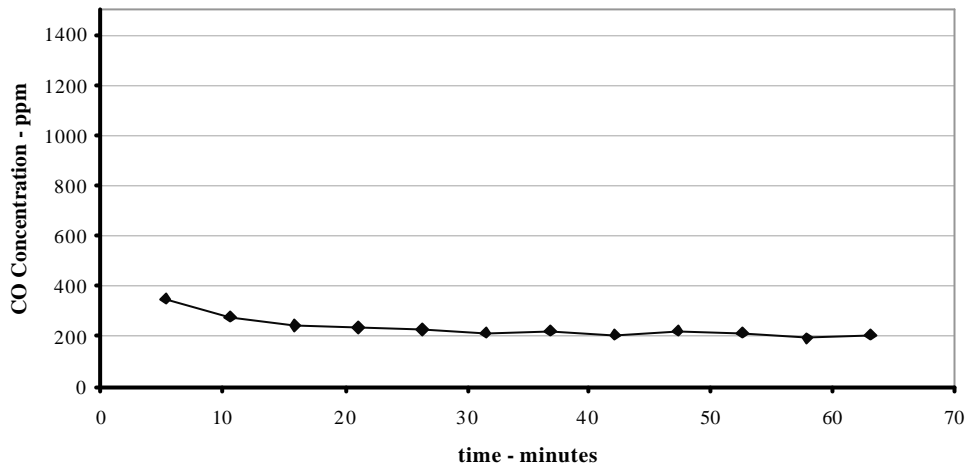


Figure A12(b)
Test 12. Concentration in the extract system

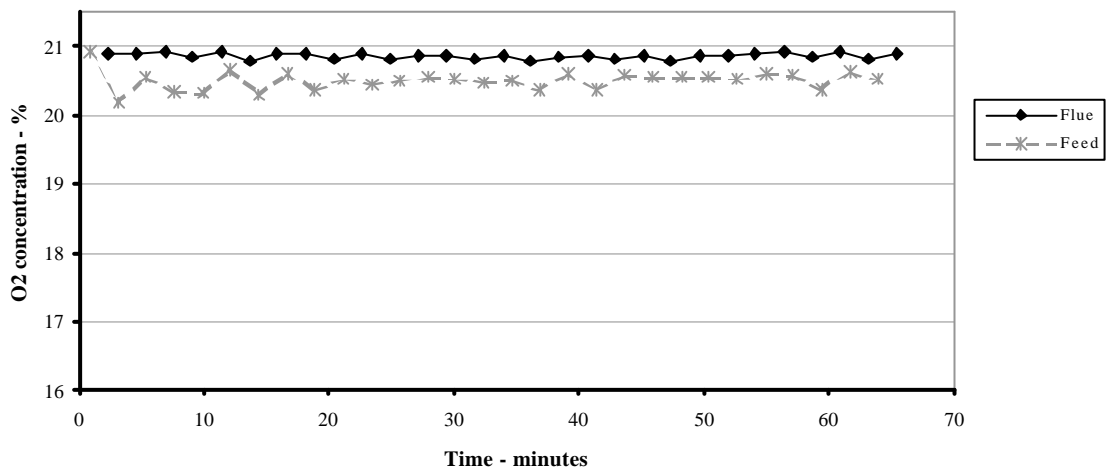
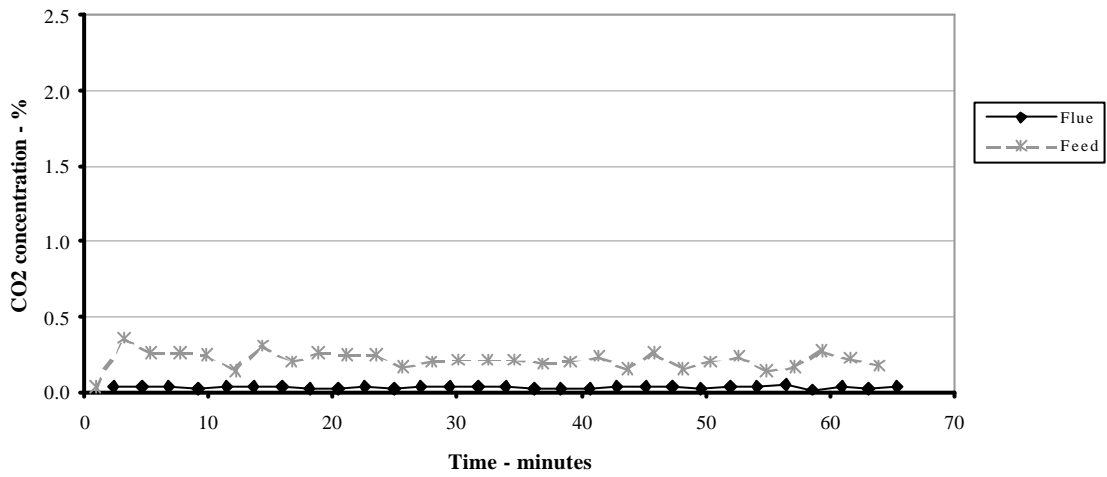
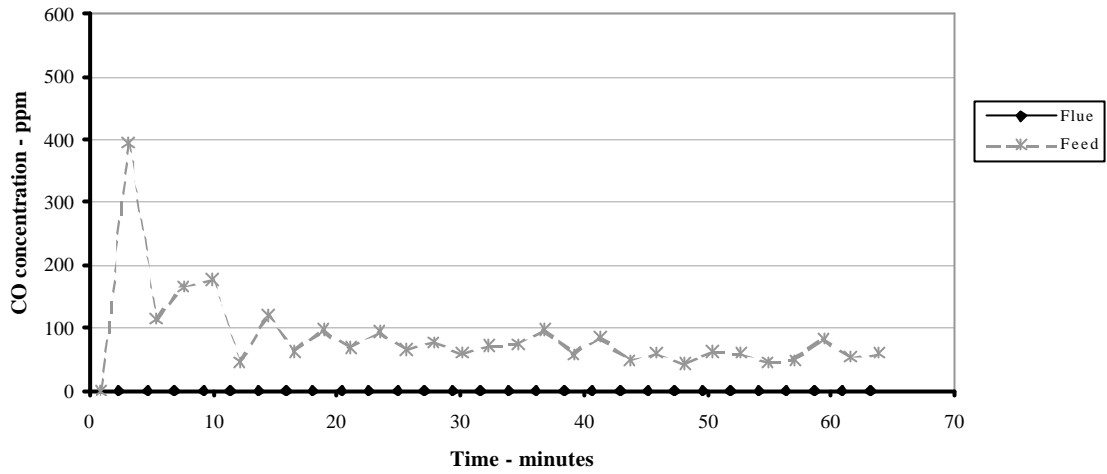


Figure A12(c)
Test 12. Concentration in the flue, and in the combustion air supply

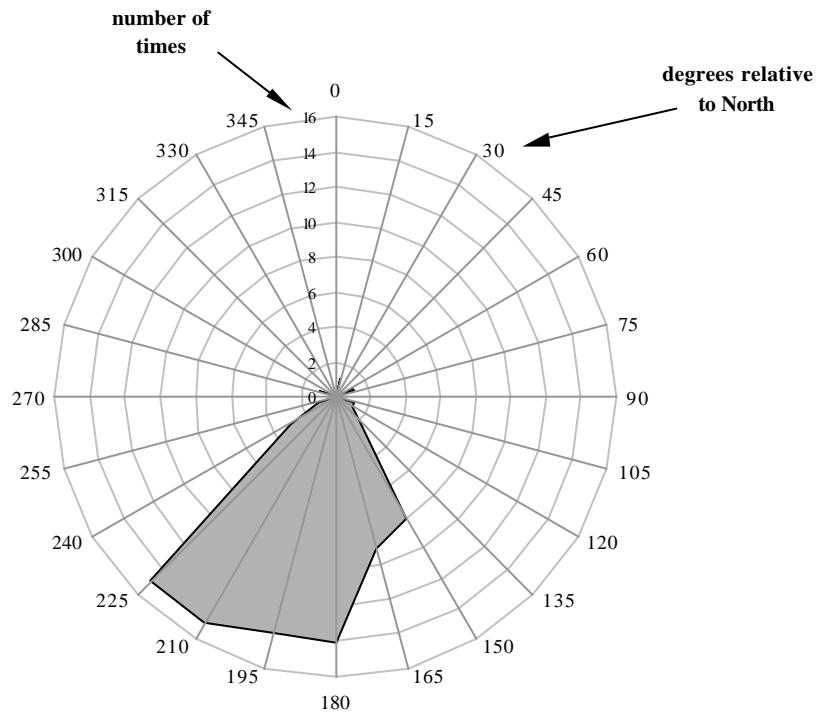
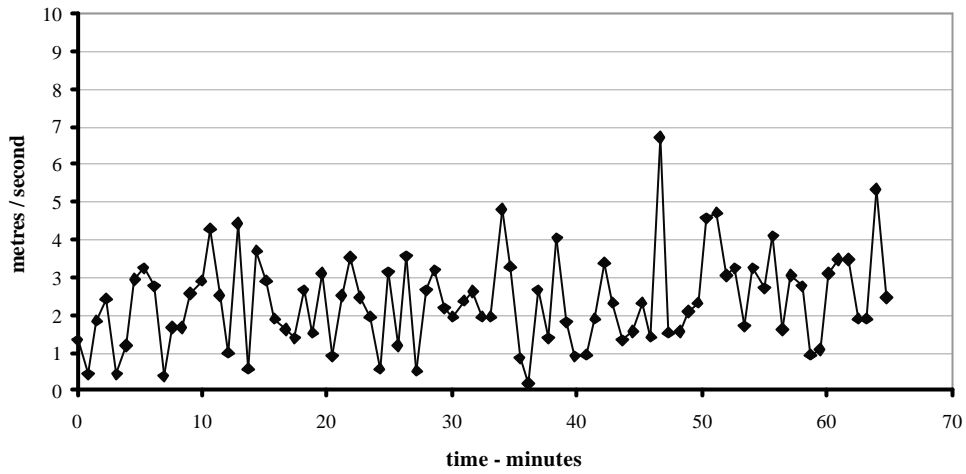


Figure A12(d)
Test 12. Wind speed and direction

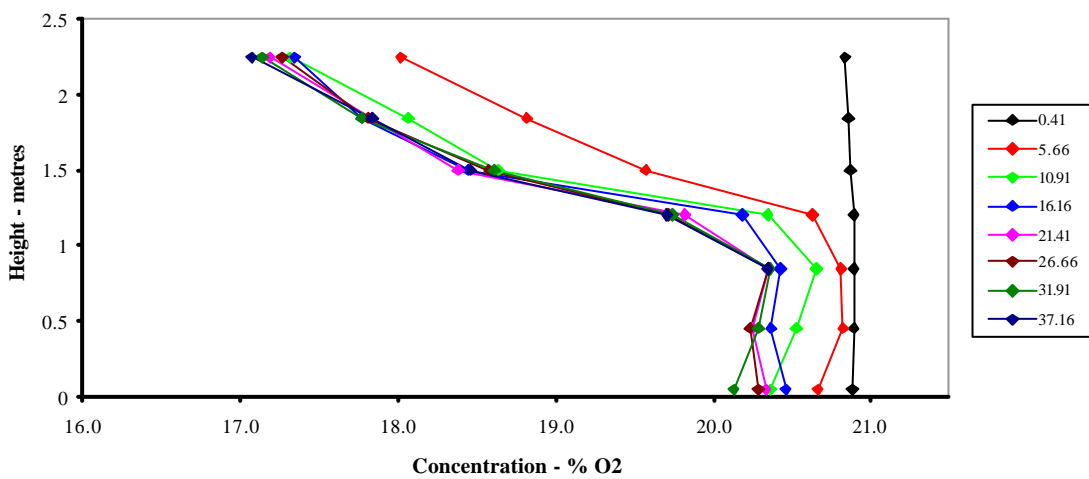
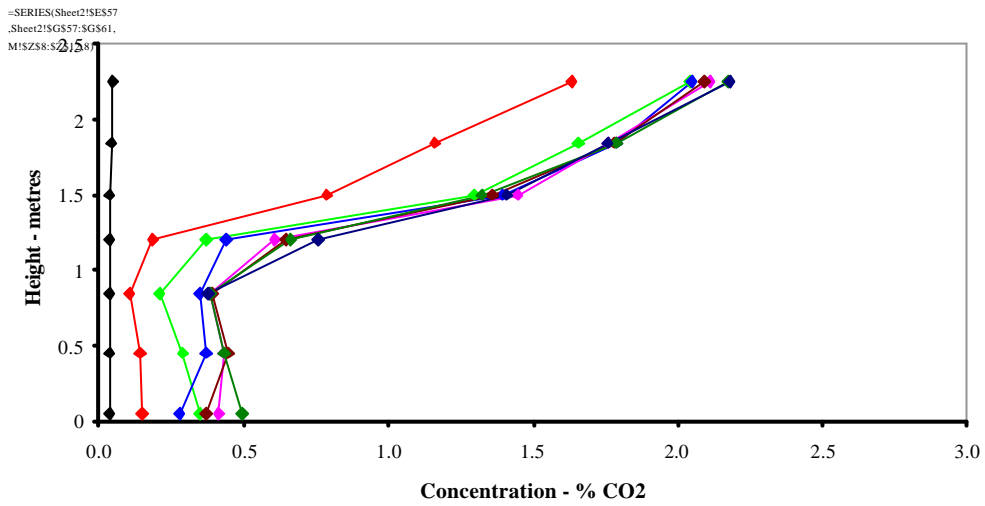
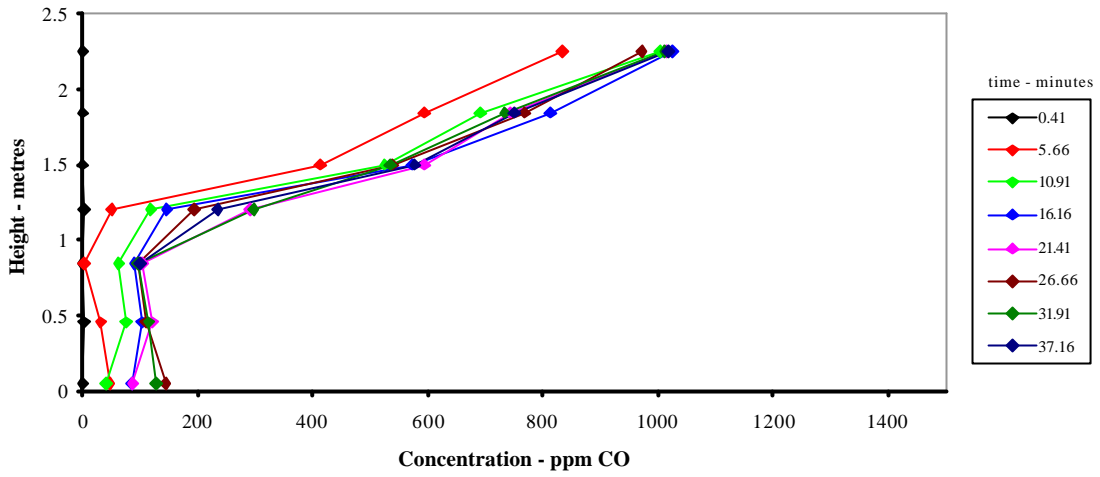


Figure A13(a)
Test 13. Concentration profiles in Room 1

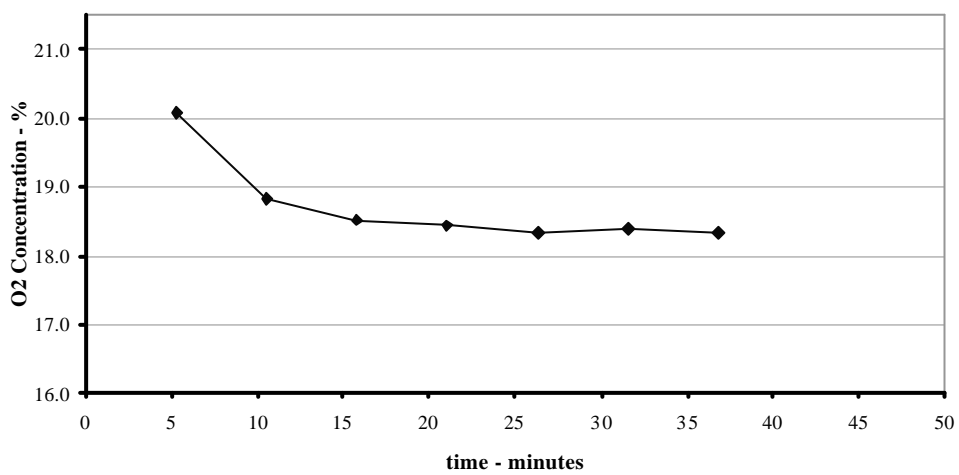
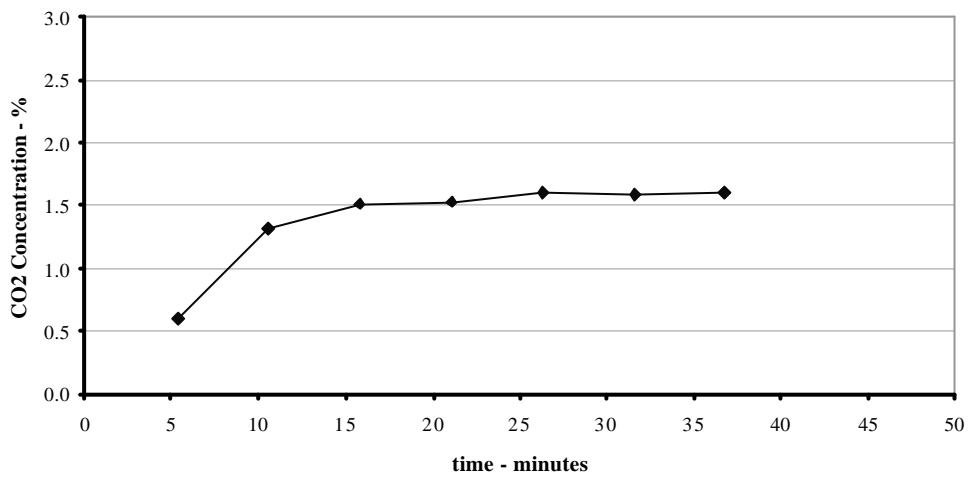
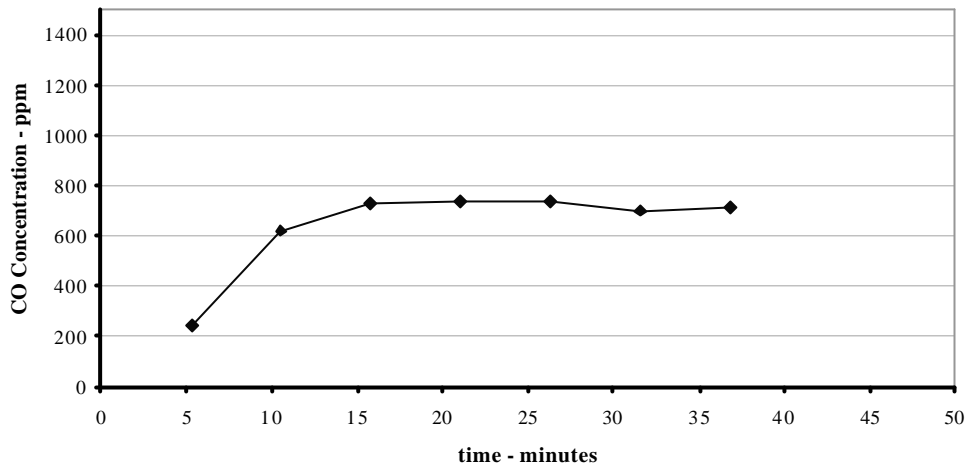


Figure A13(b)
Test 13. Concentration in the extract system

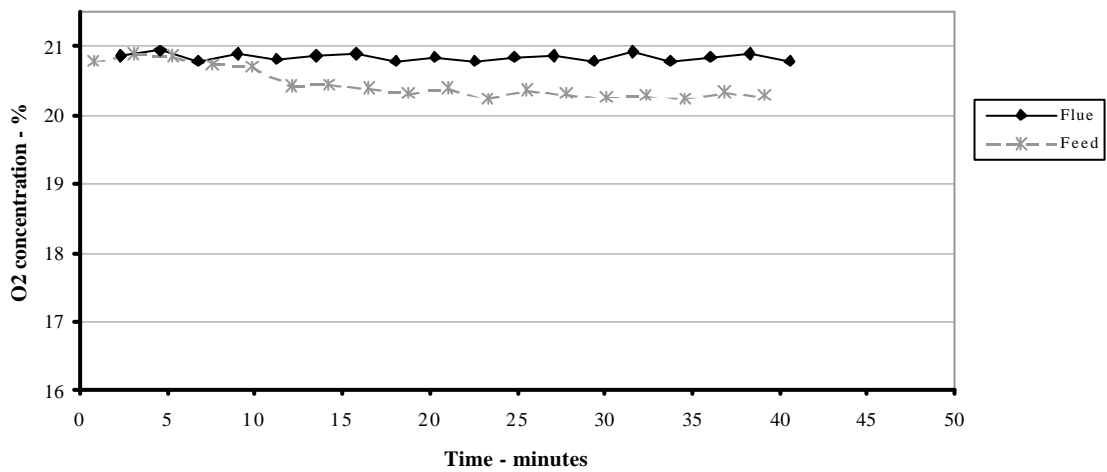
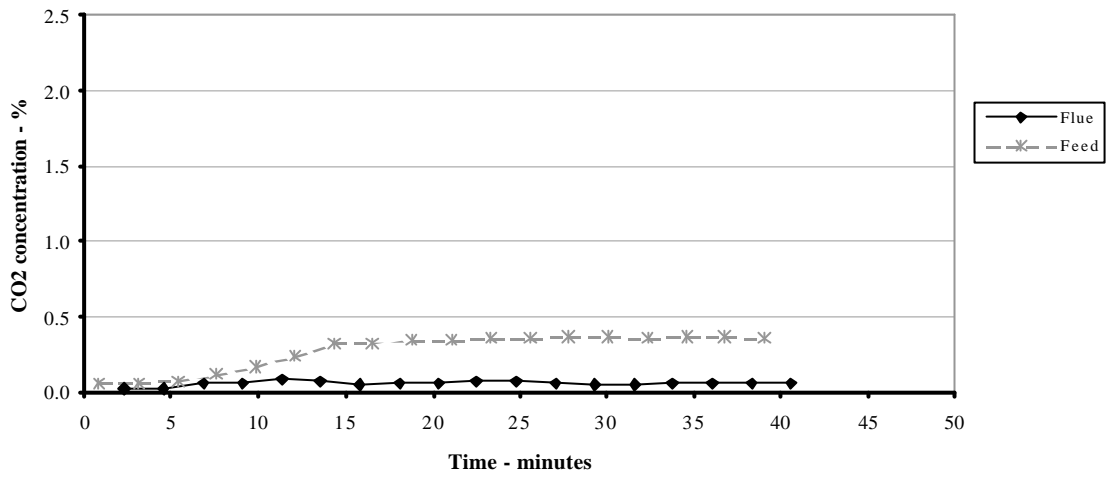
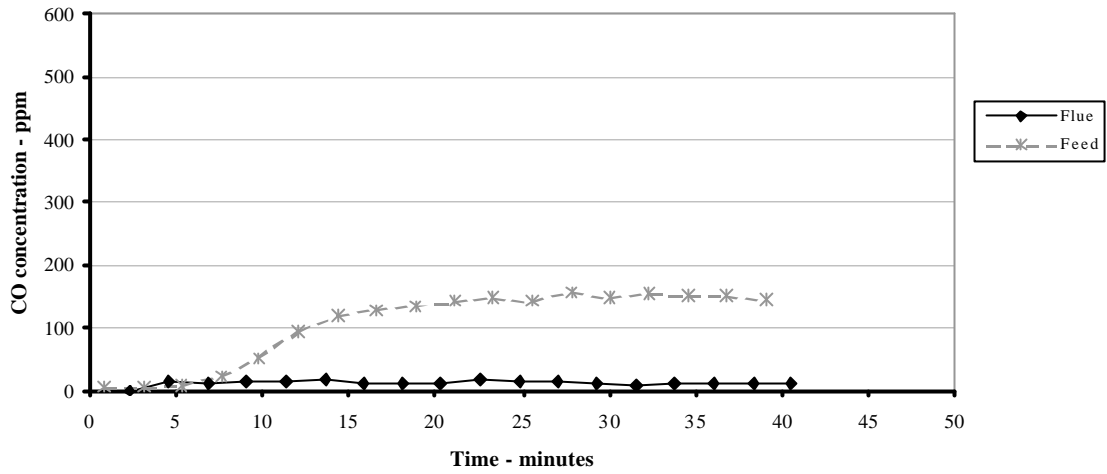


Figure A13(c)
Test 13. Concentration in the flue, and in the combustion air supply

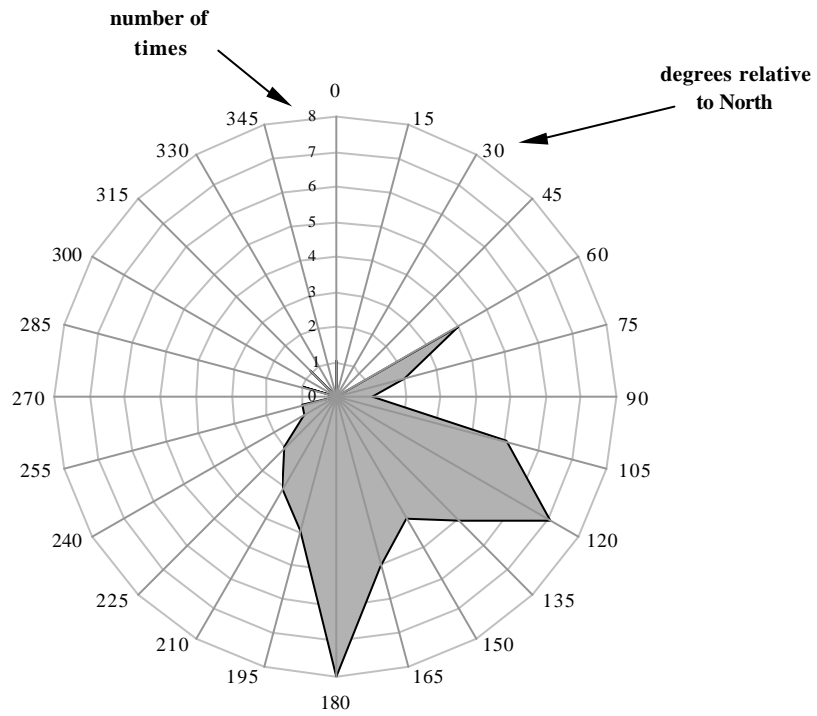
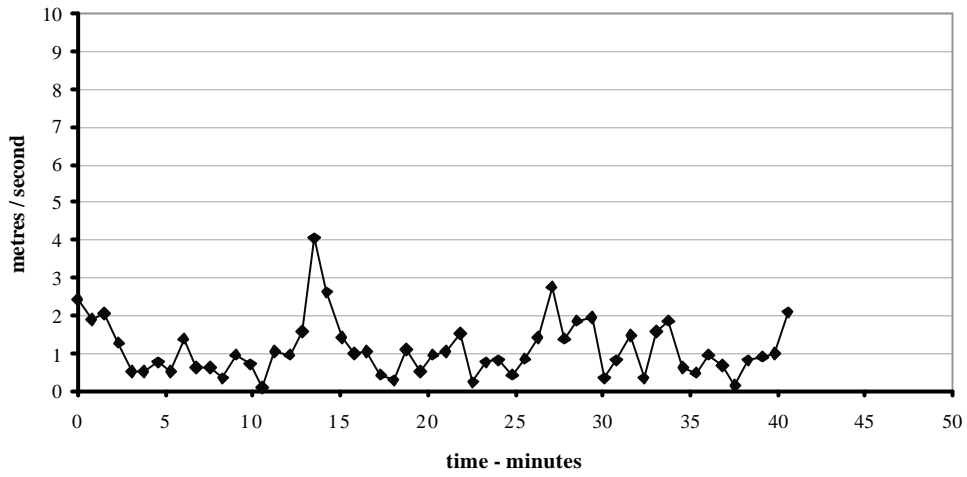


Figure A13(d)
Test 13. Wind speed and direction

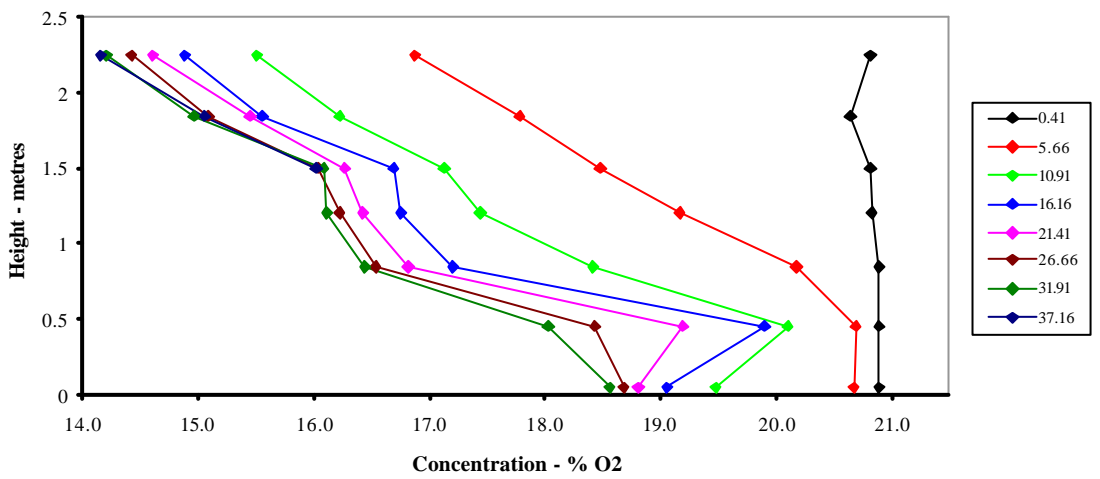
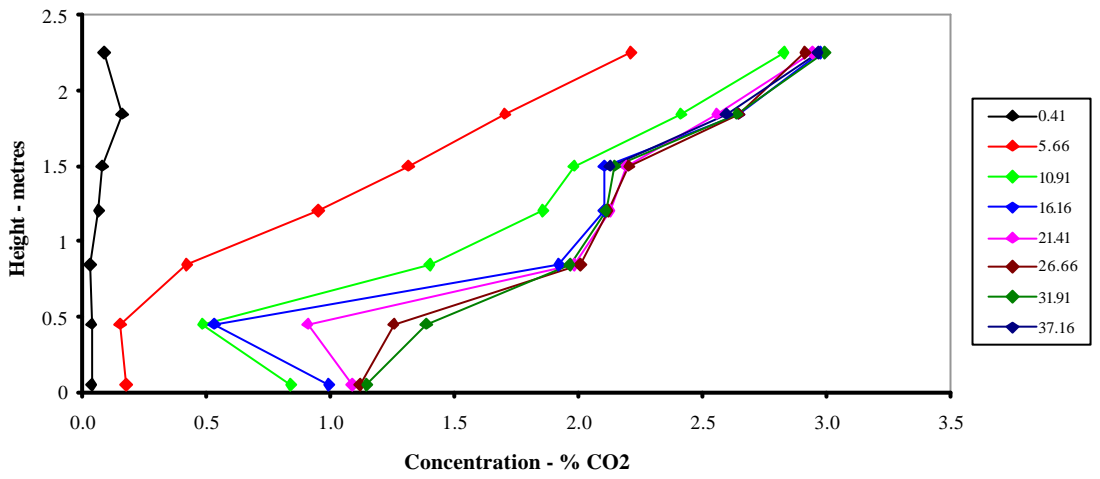
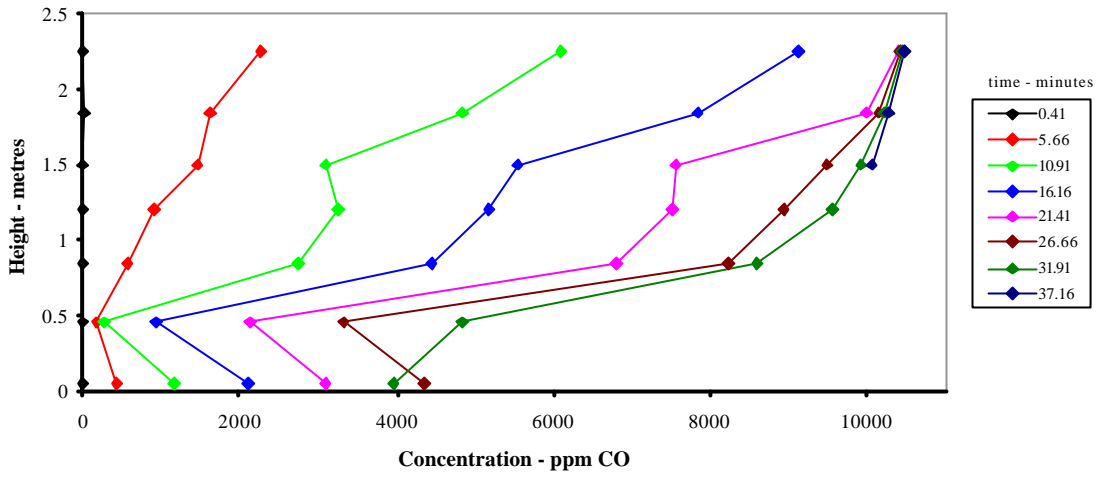


Figure A14(a)
Test 14. Concentration profiles in Room 1

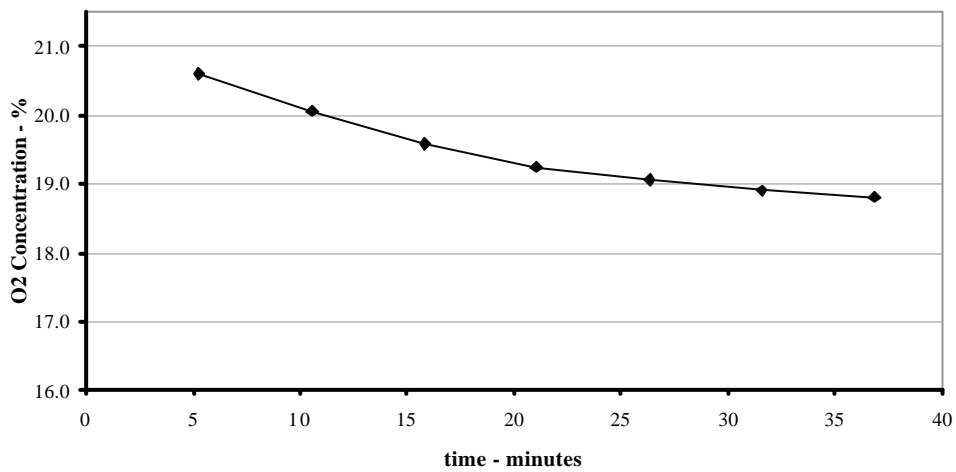
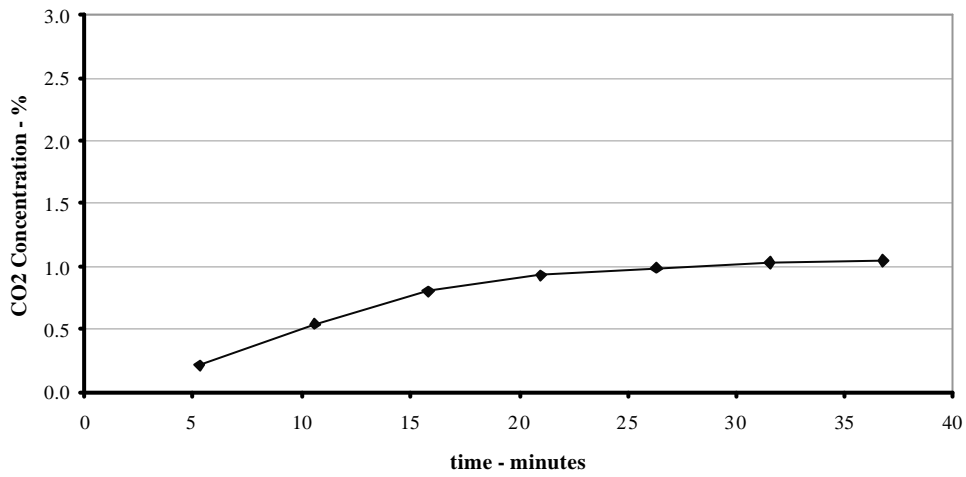
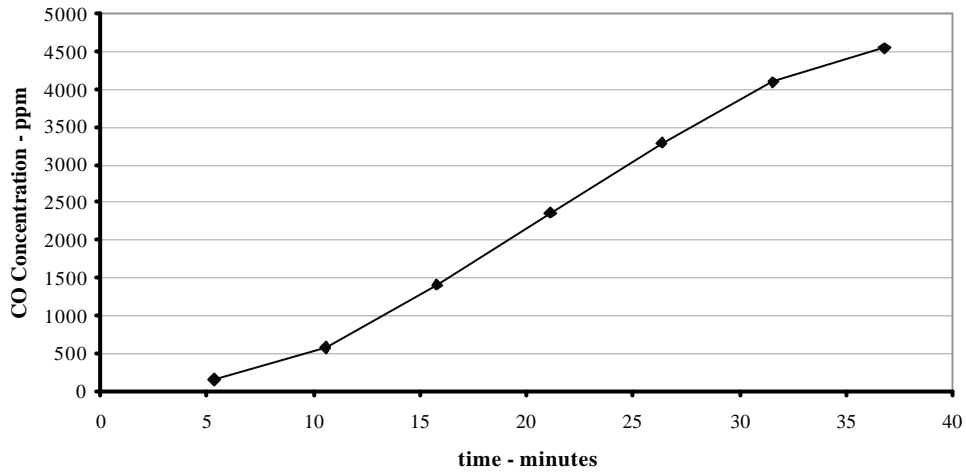


Figure A14(b)
Test 14. Concentration in the extract system

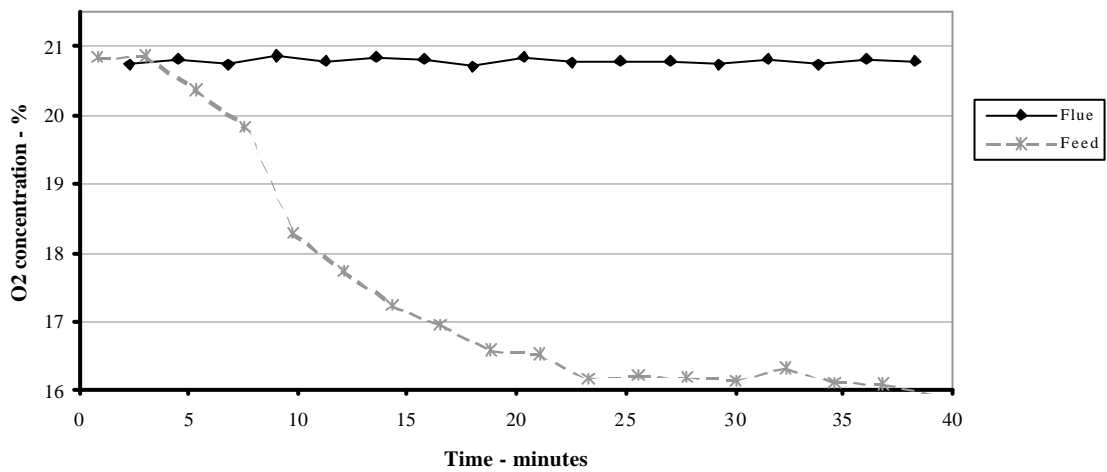
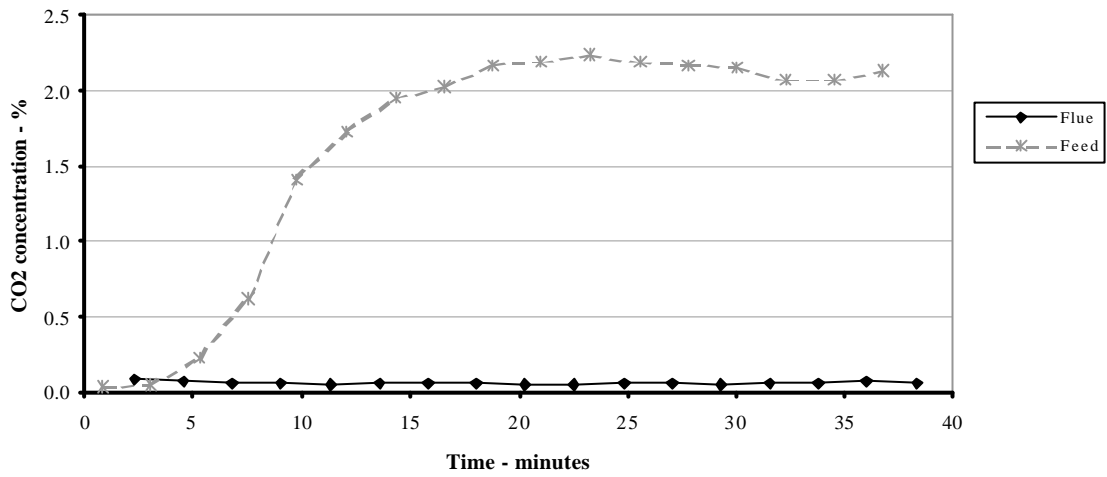
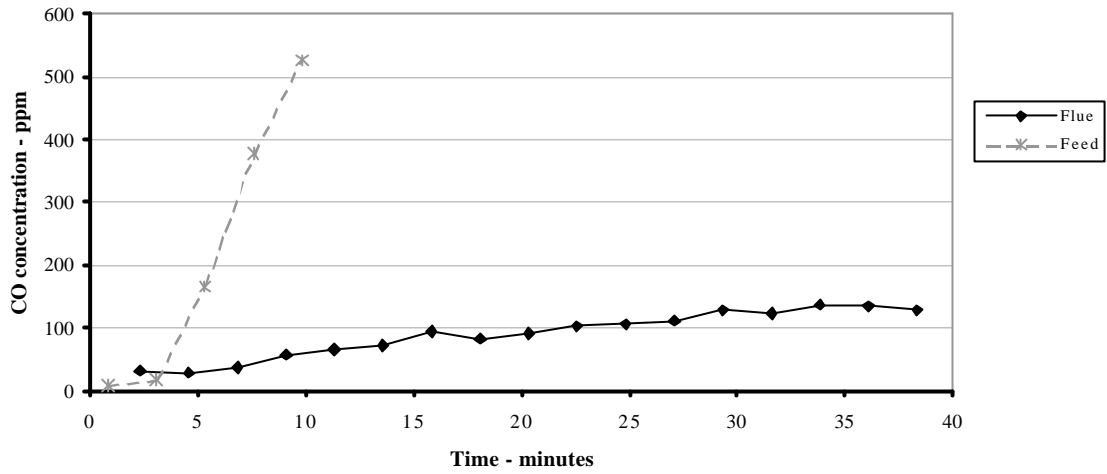


Figure A14(c)
Test 14. Concentration in the flue, and in the combustion air supply

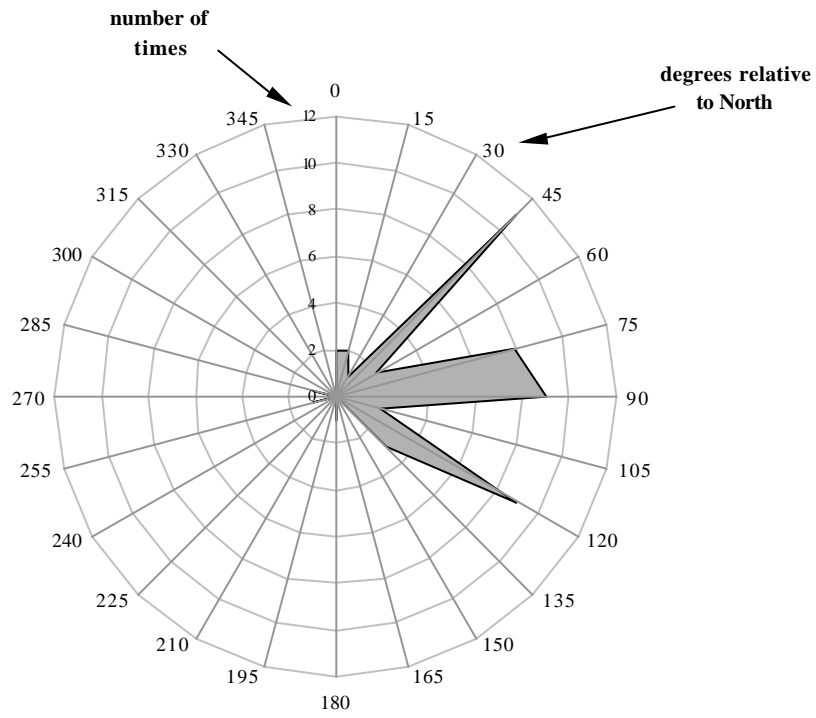
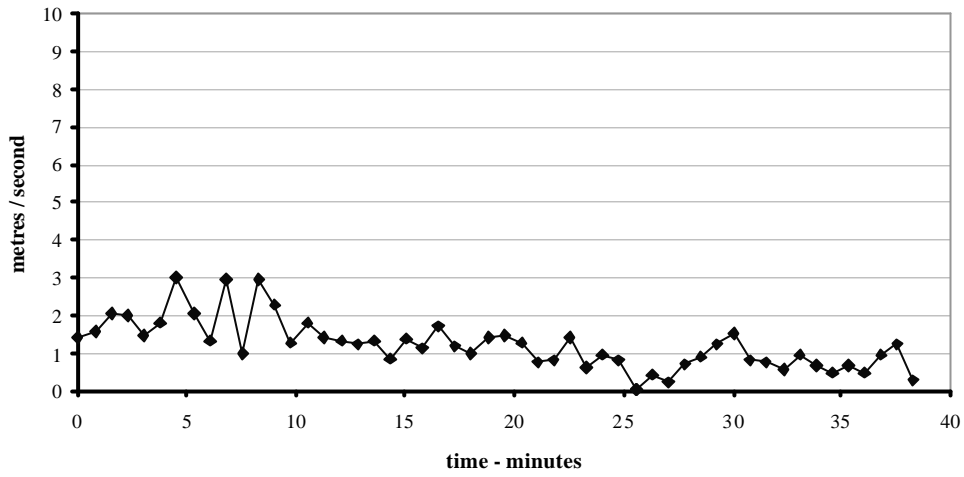


Figure A14(d)
Test 14. Wind speed and direction

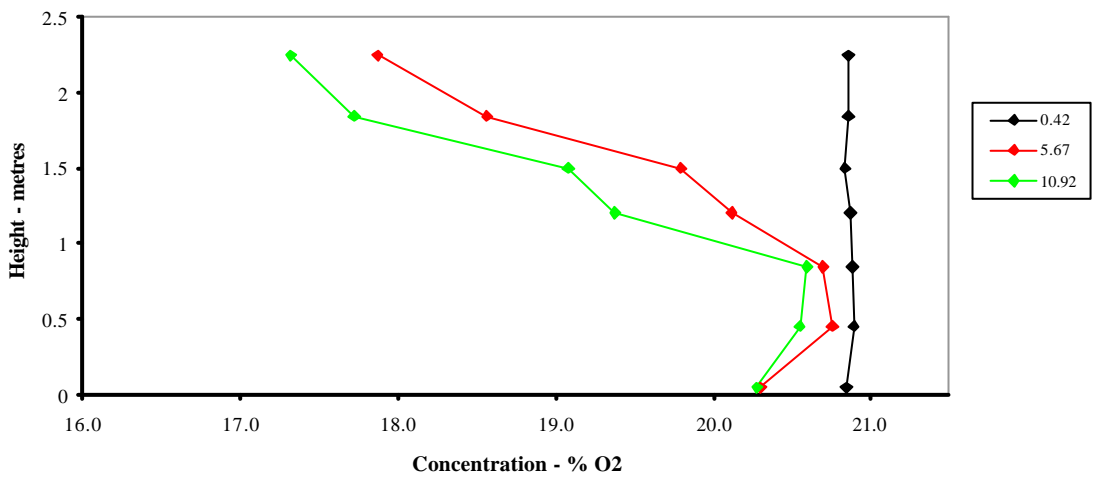
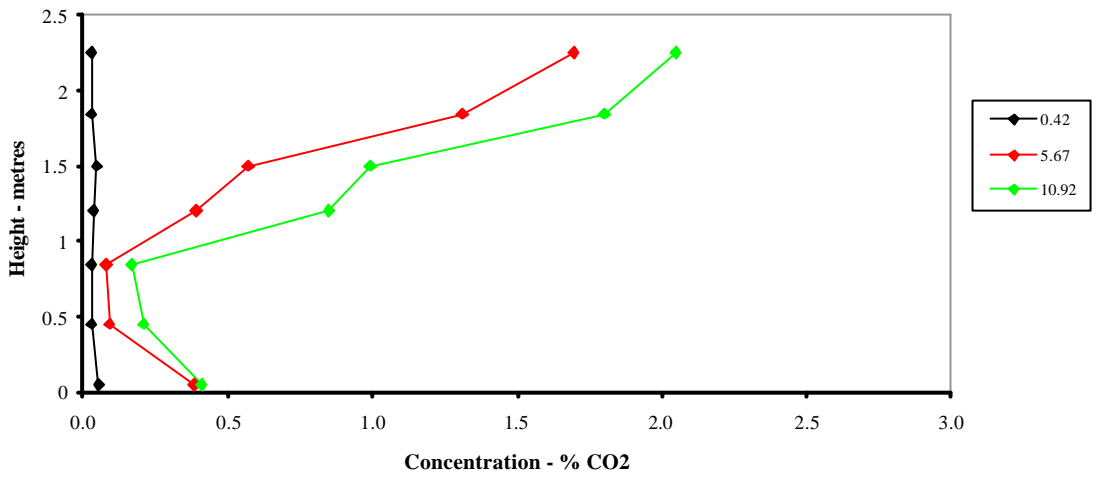
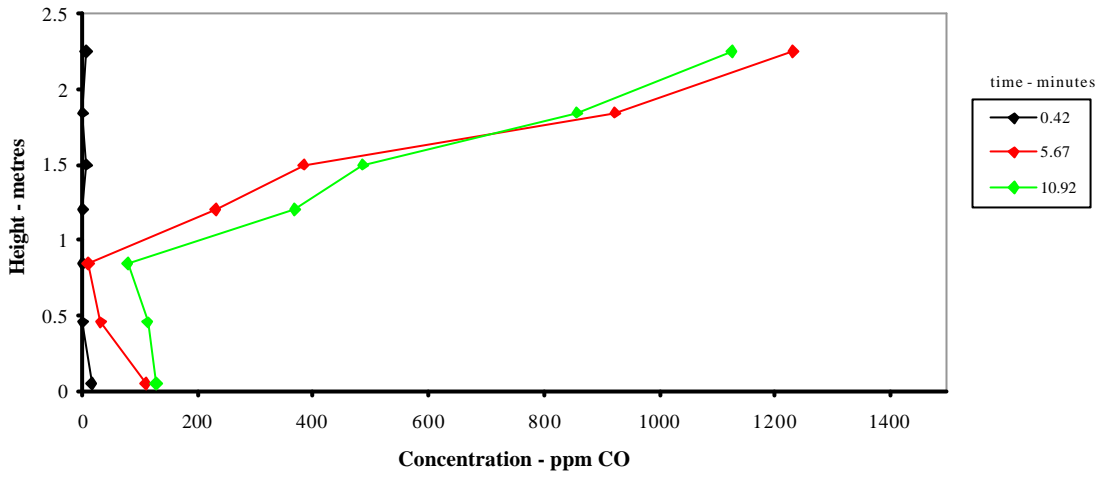


Figure A15(a)
Test 15. Concentration profiles in Room 1

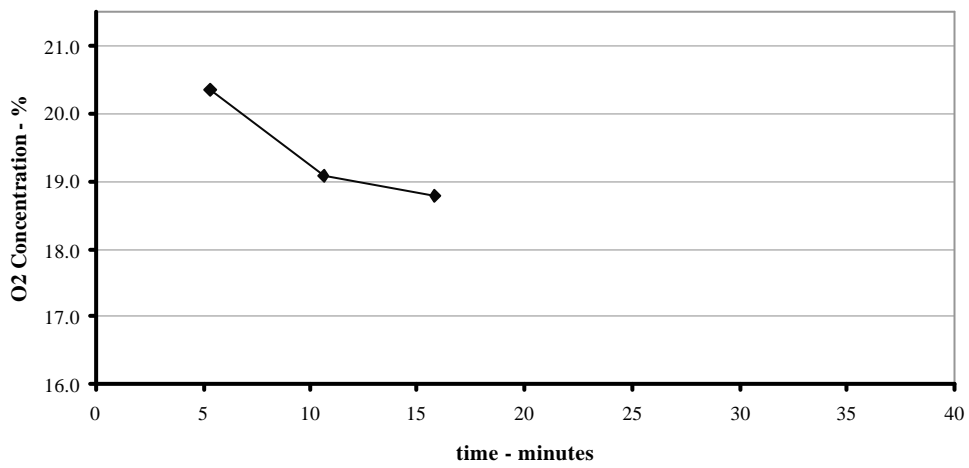
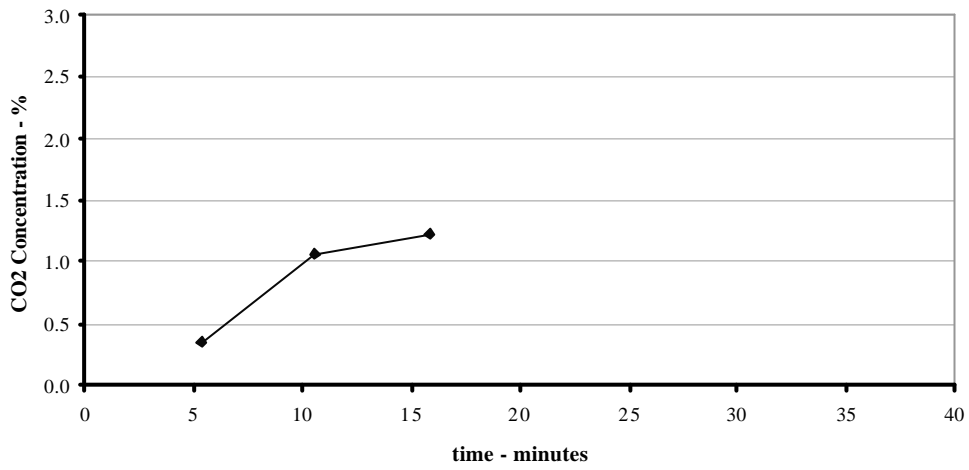
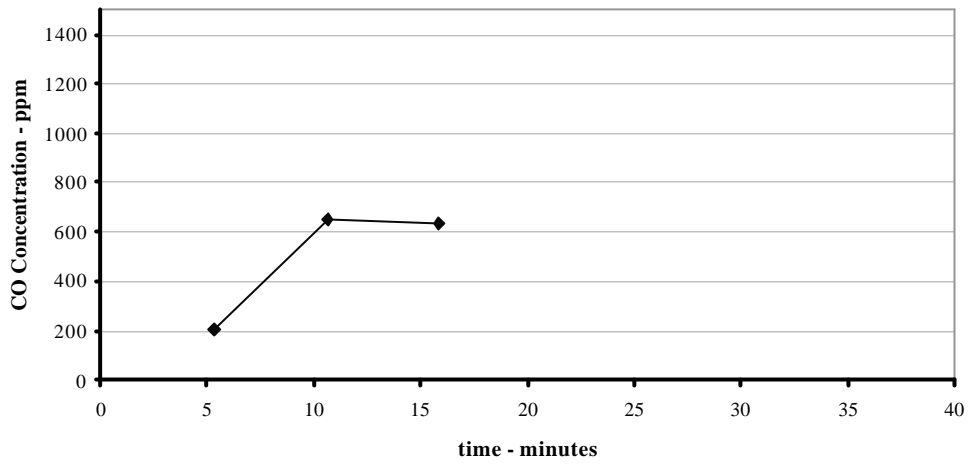


Figure A15(b)
Test 15. Concentration in the extract system

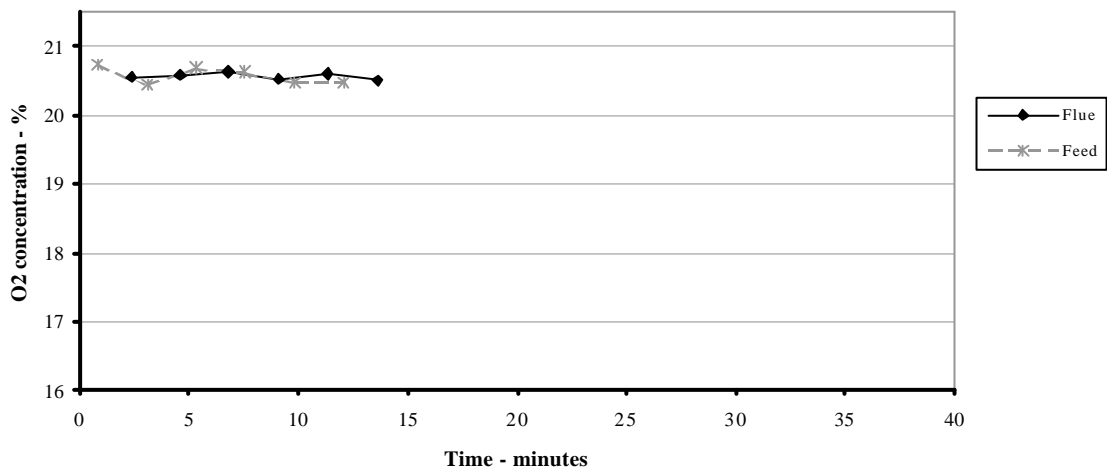
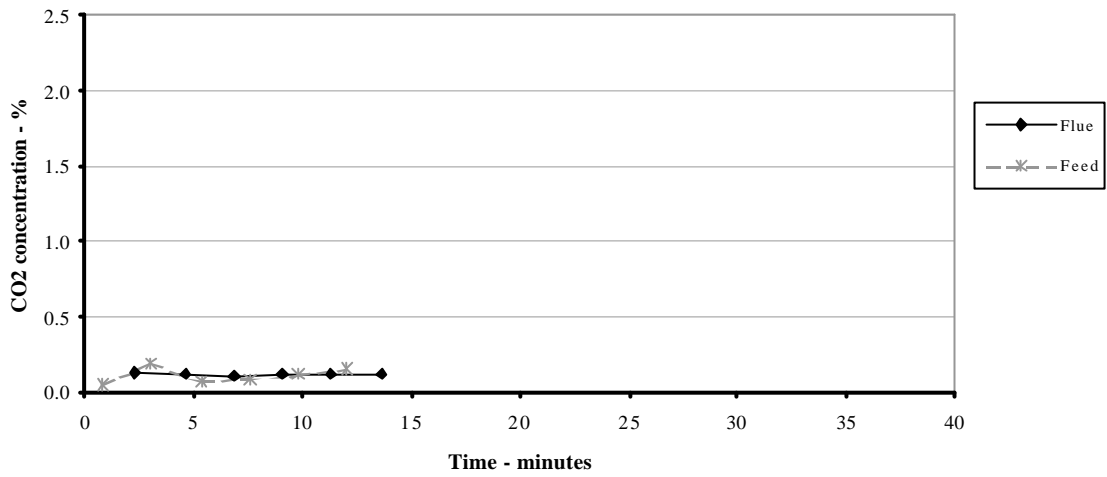
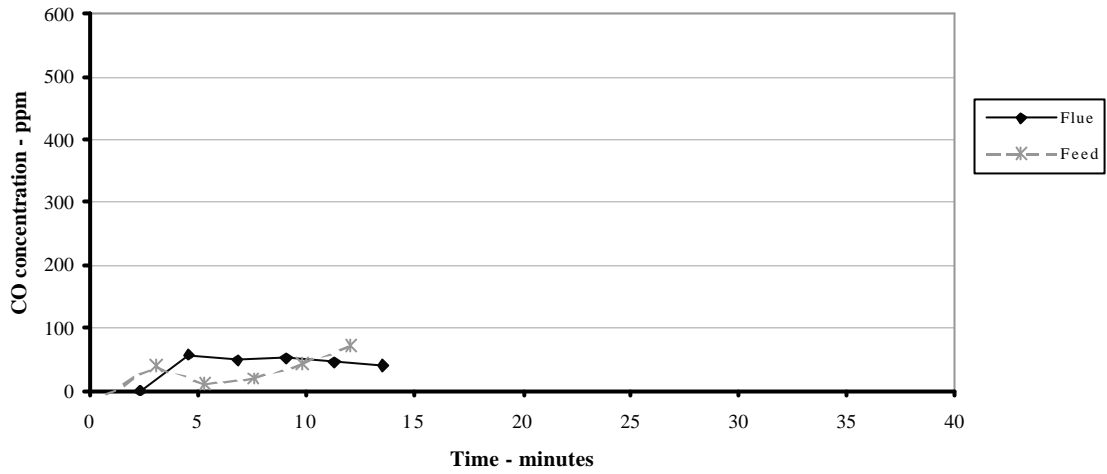


Figure A15(c)
Test 15. Concentration in the flue, and in the combustion air supply

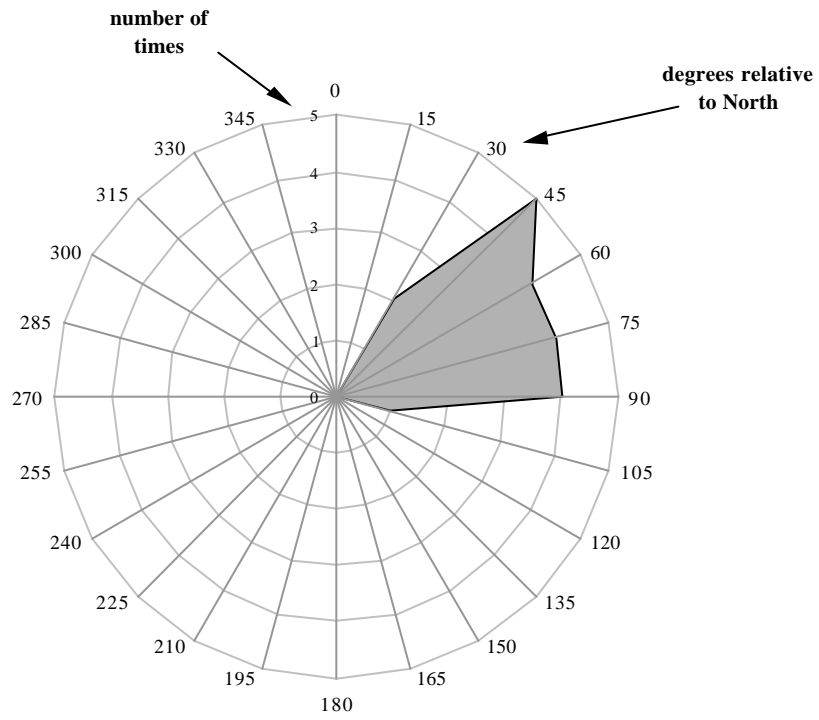
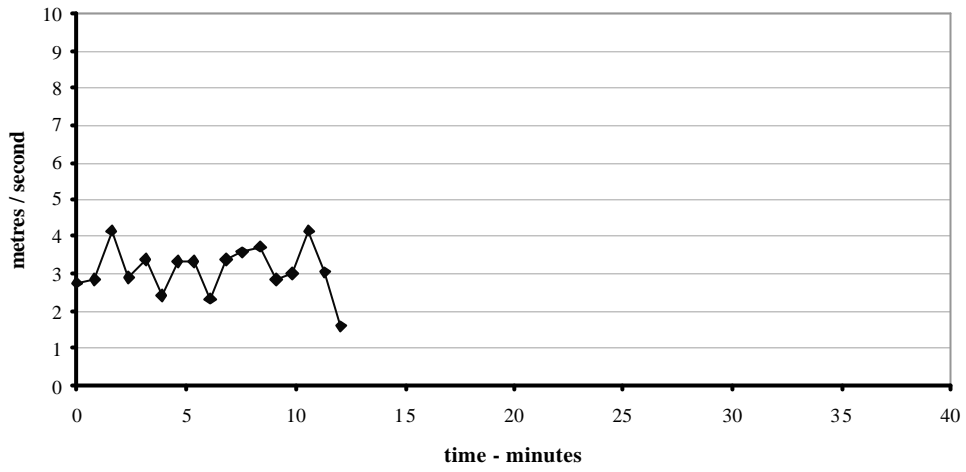


Figure A15(d)
Test 15. Wind speed and direction

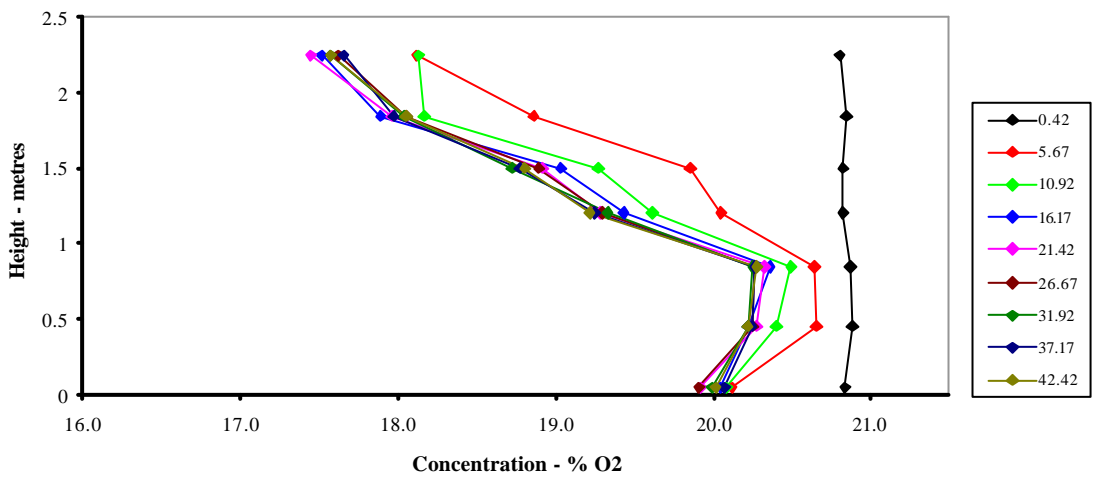
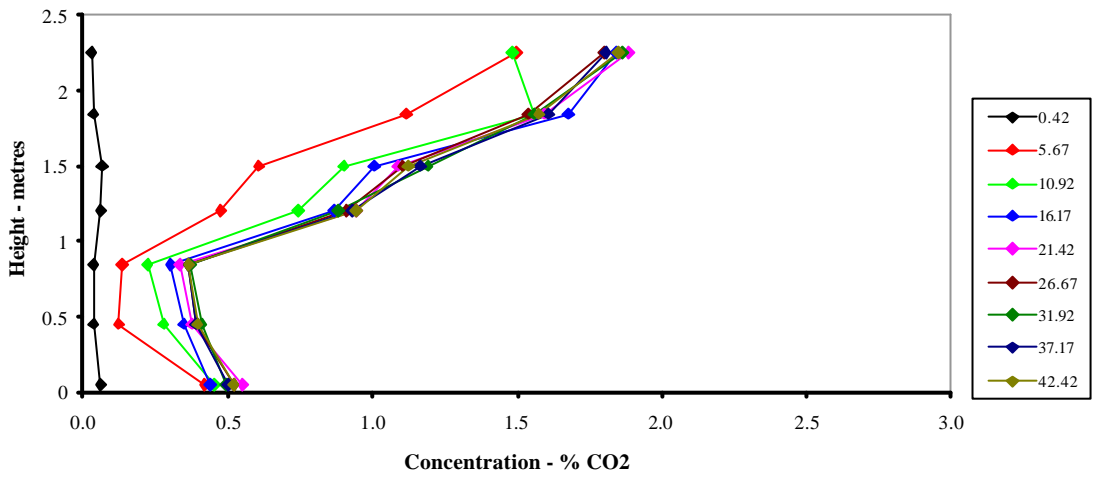
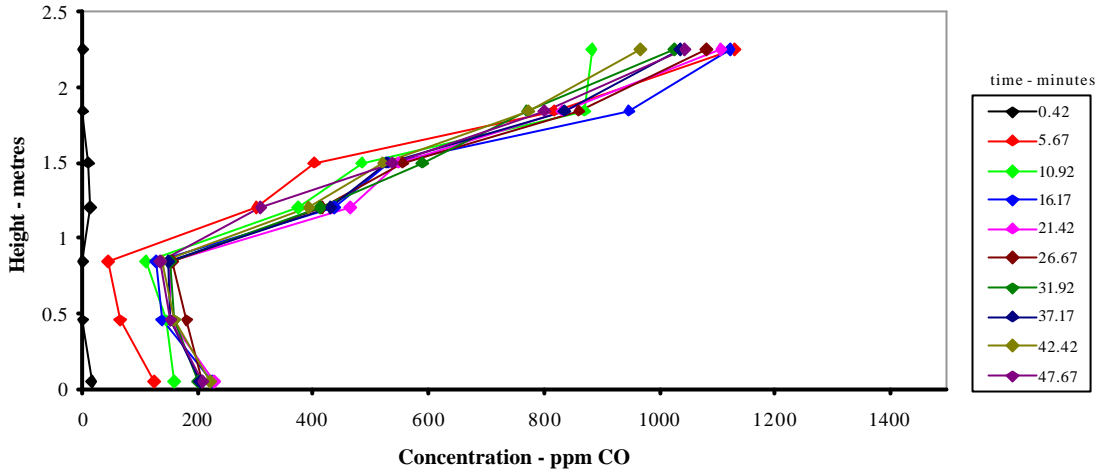


Figure A16(a)
Test 16. Concentration profiles in Room 1

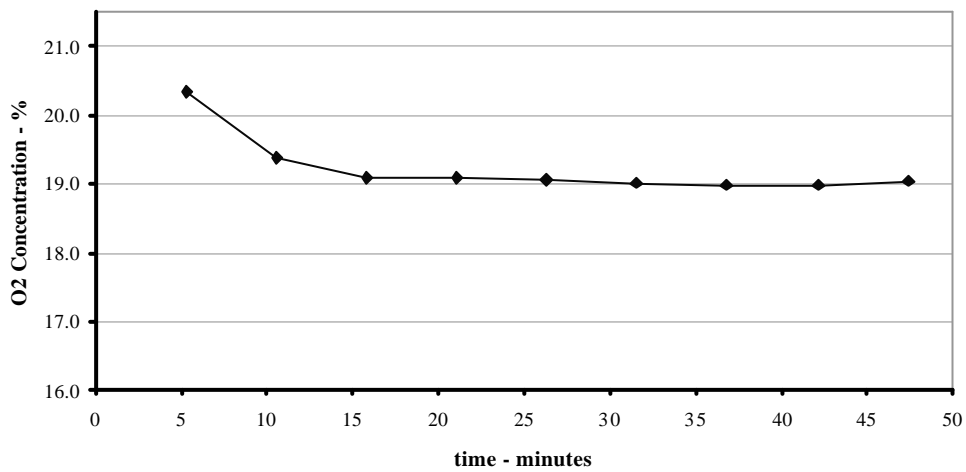
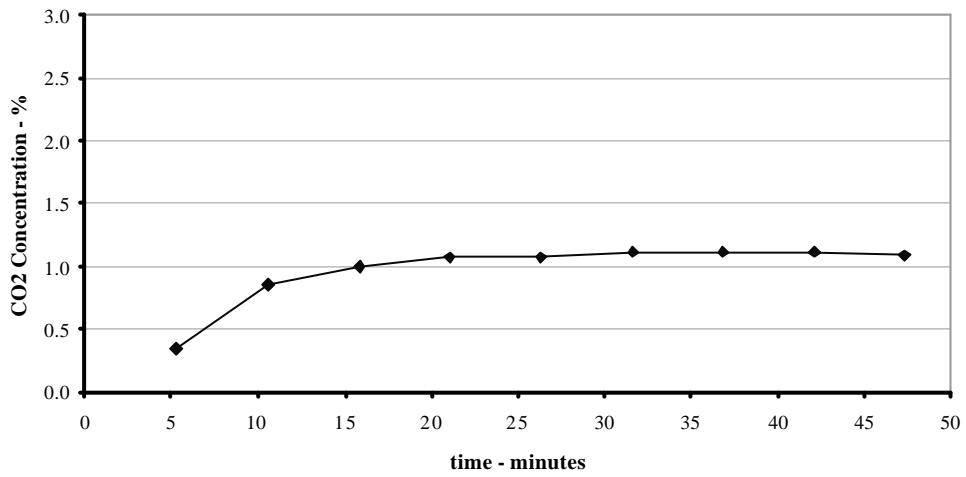
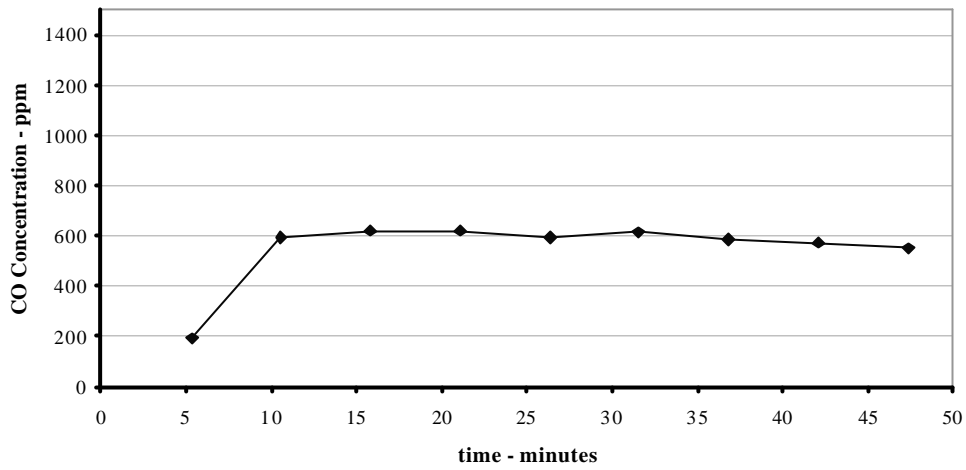


Figure A16(b)
Test 16. Concentration in the extract system

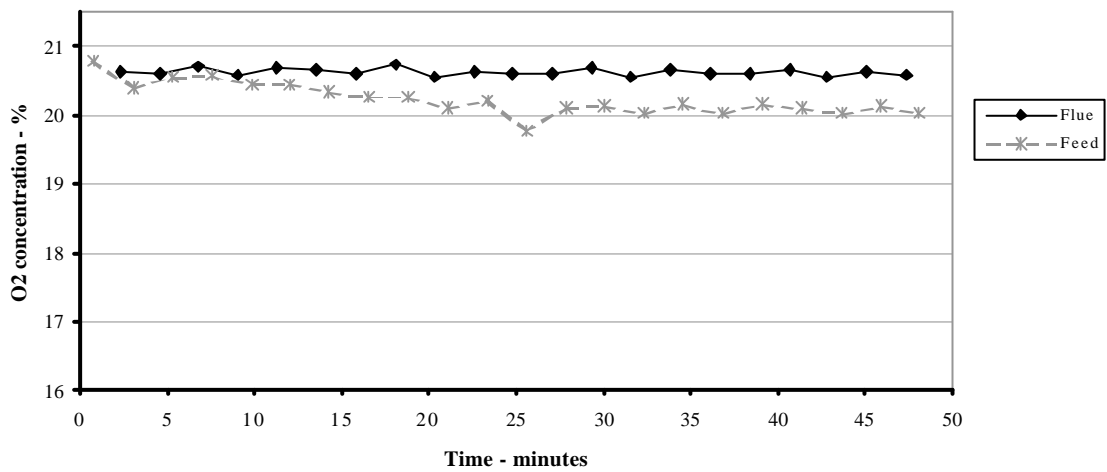
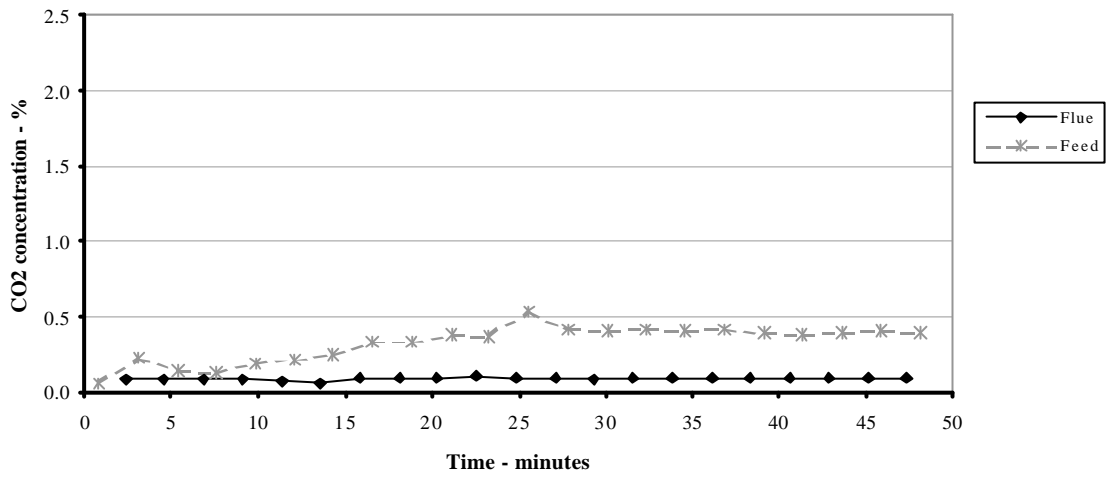
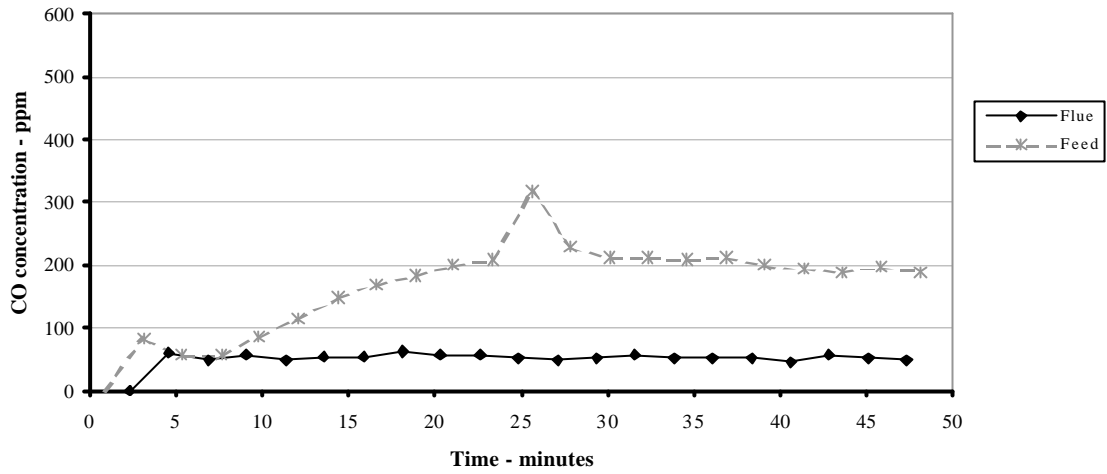


Figure A16(c)
Test 16. Concentration in the flue, and in the combustion air supply

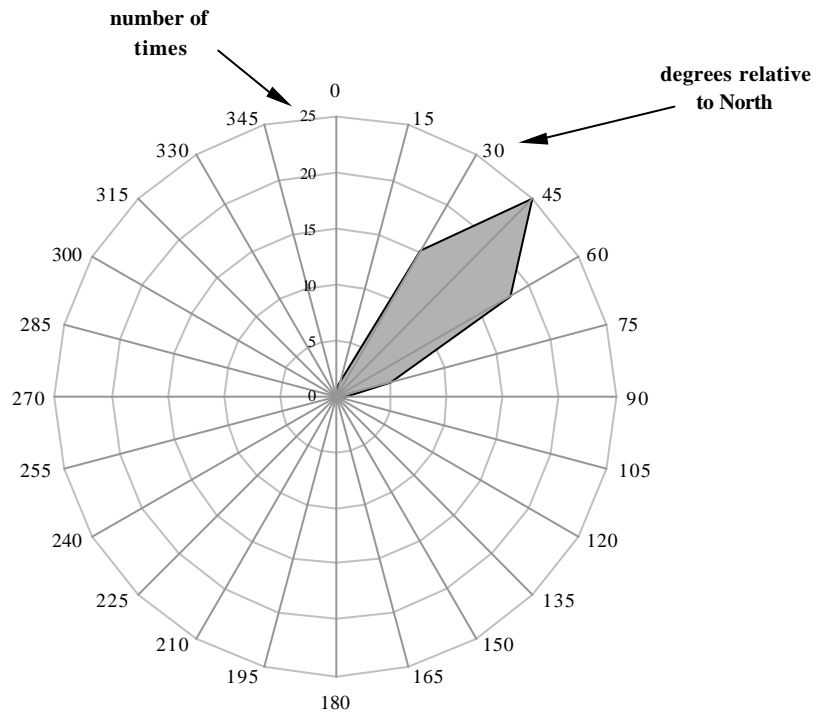
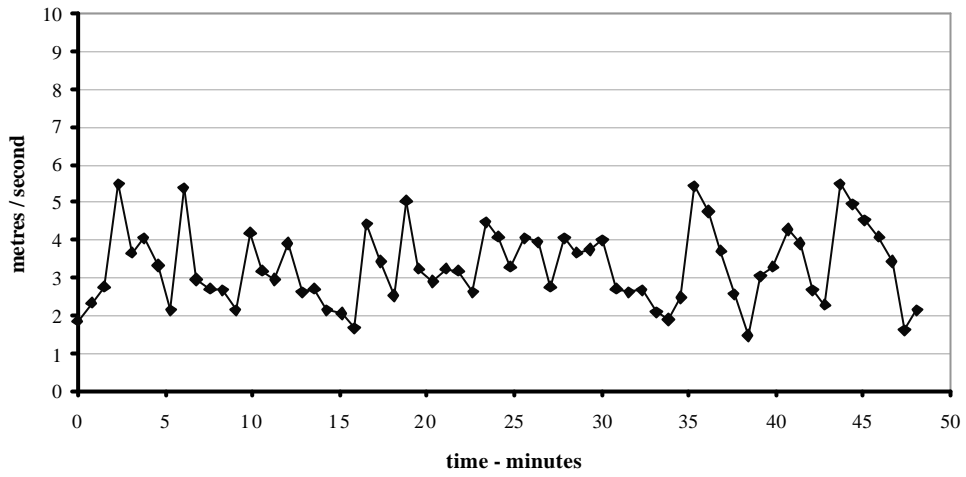


Figure A16(d)
Test 16. Wind speed and direction

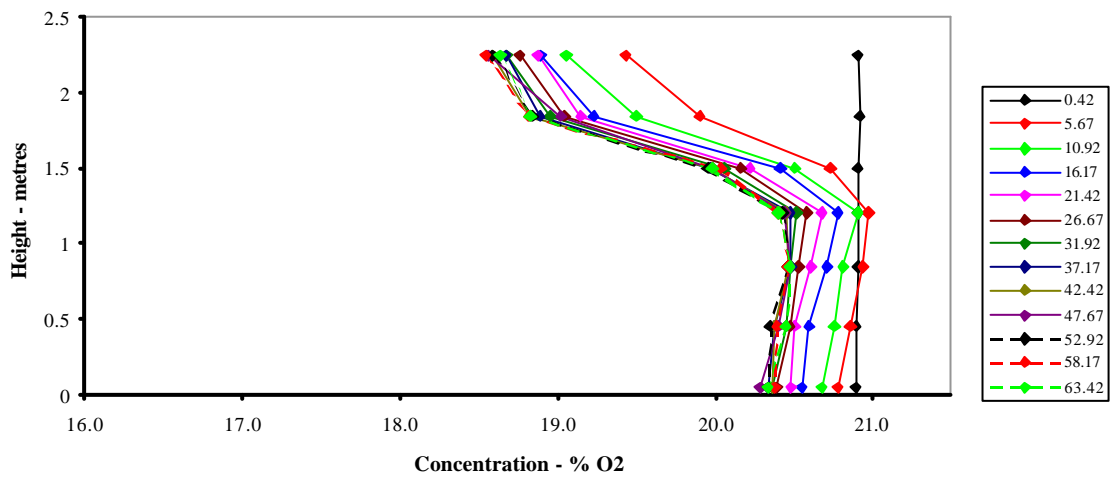
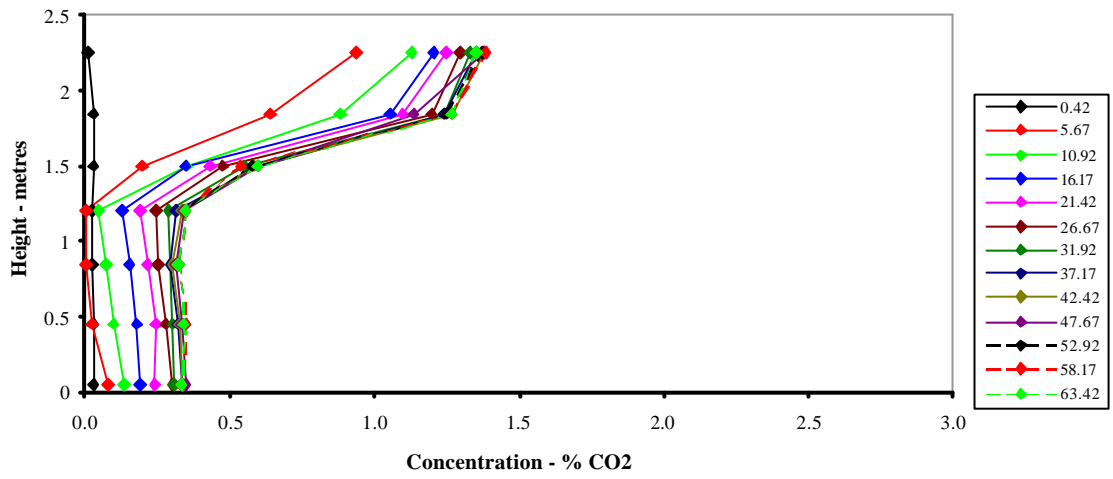
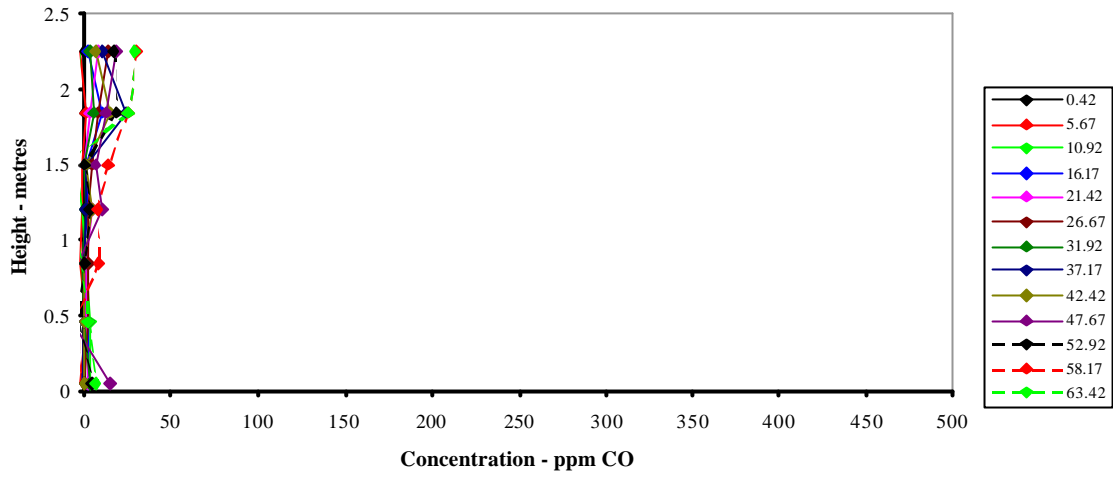


Figure A17(a)
Test 17. Concentration profiles in Room 1

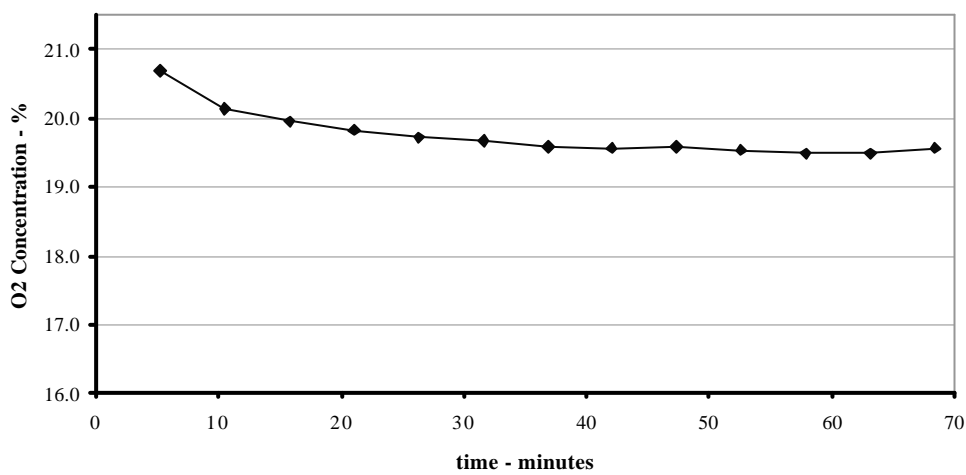
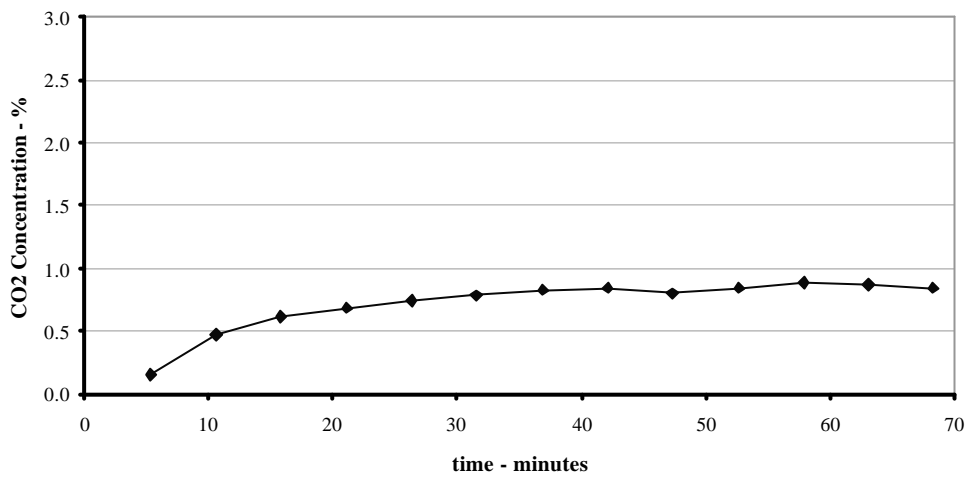
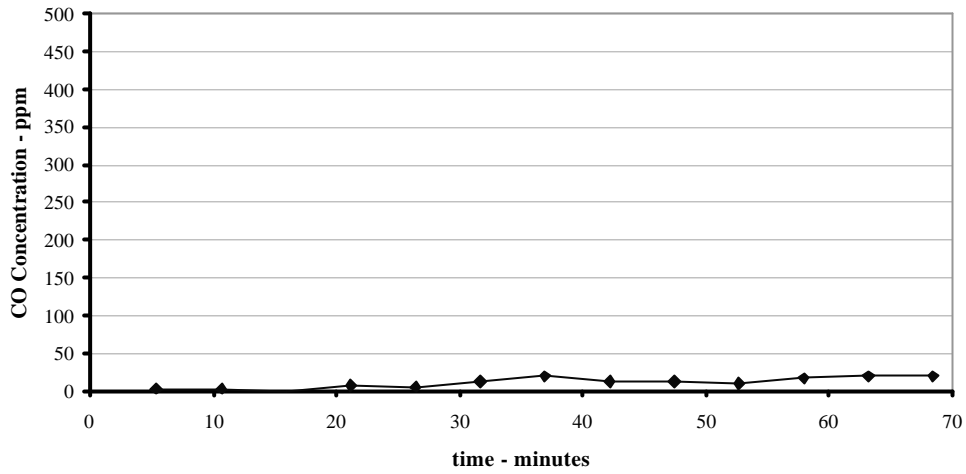


Figure A17(b)
Test 17. Concentration in the extract system

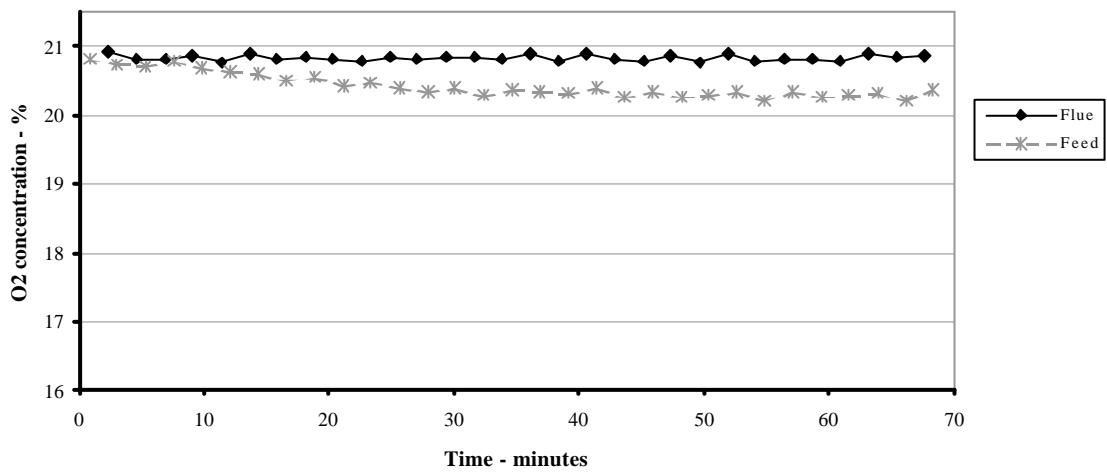
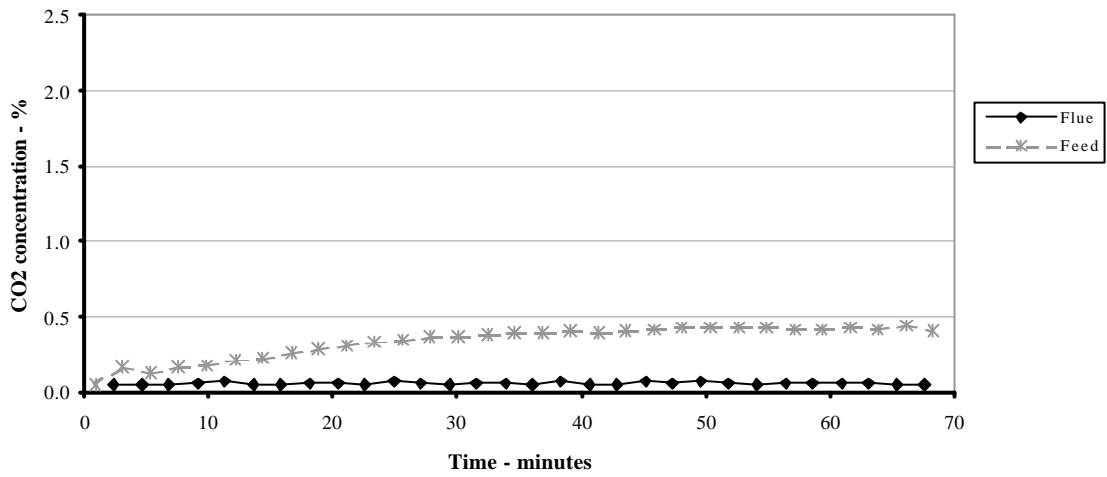
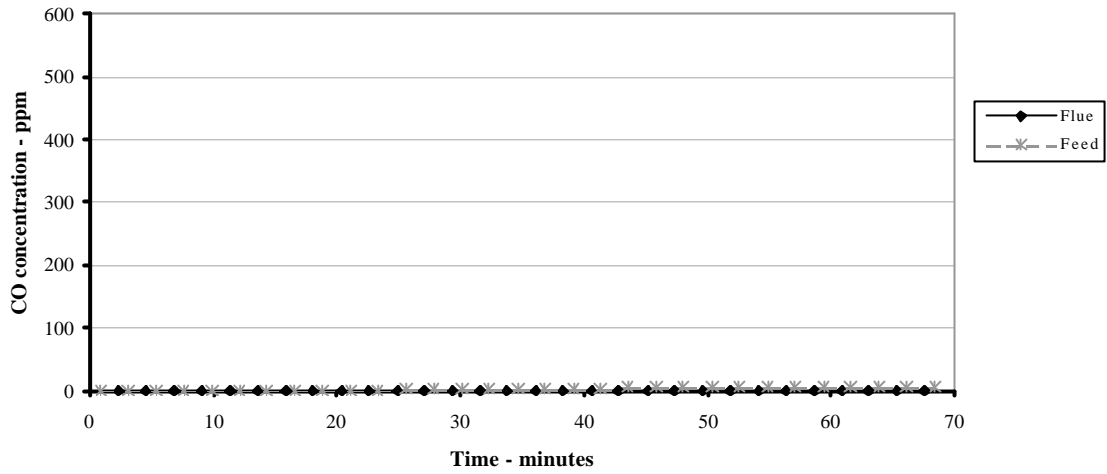


Figure A17(c)
Test 17. Concentration in the flue, and in the combustion air supply

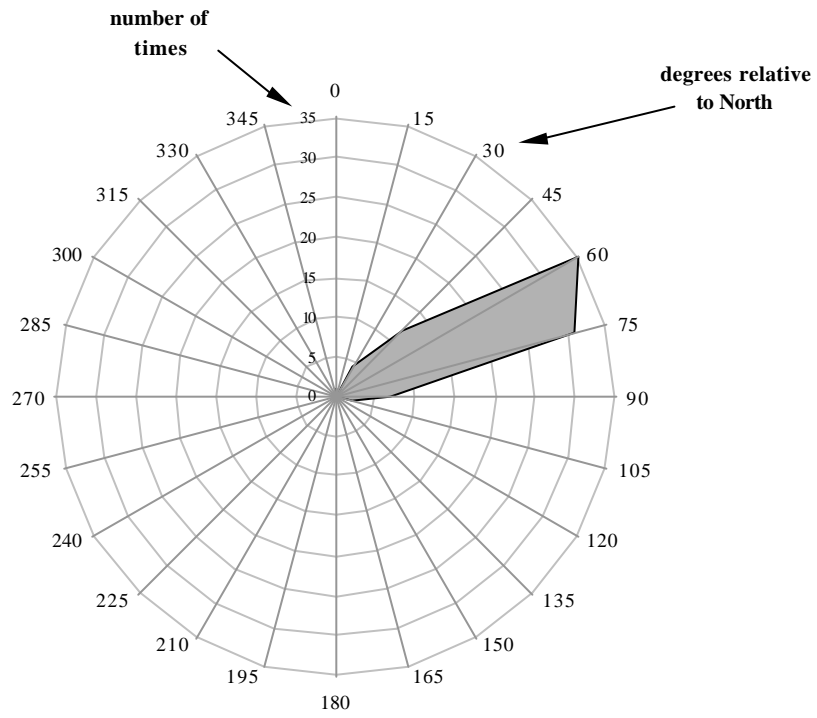
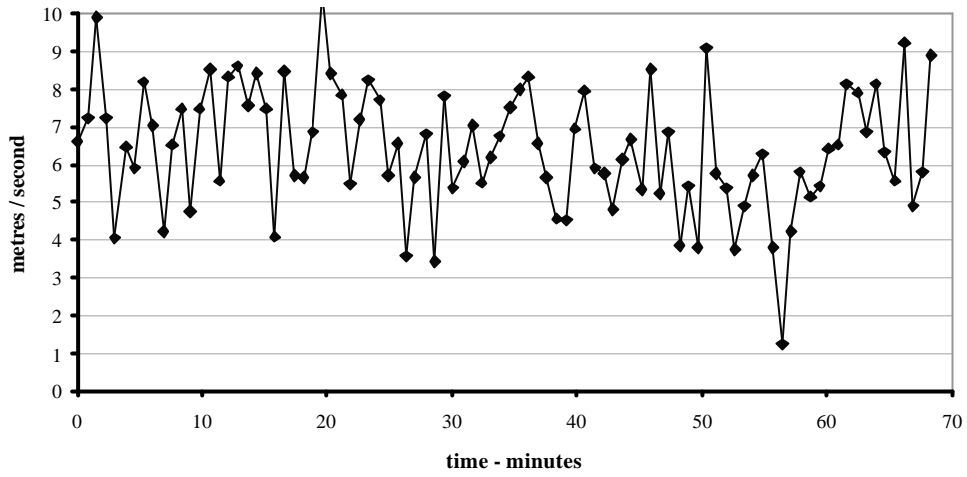


Figure A17(d)
Test 17. Wind speed and direction

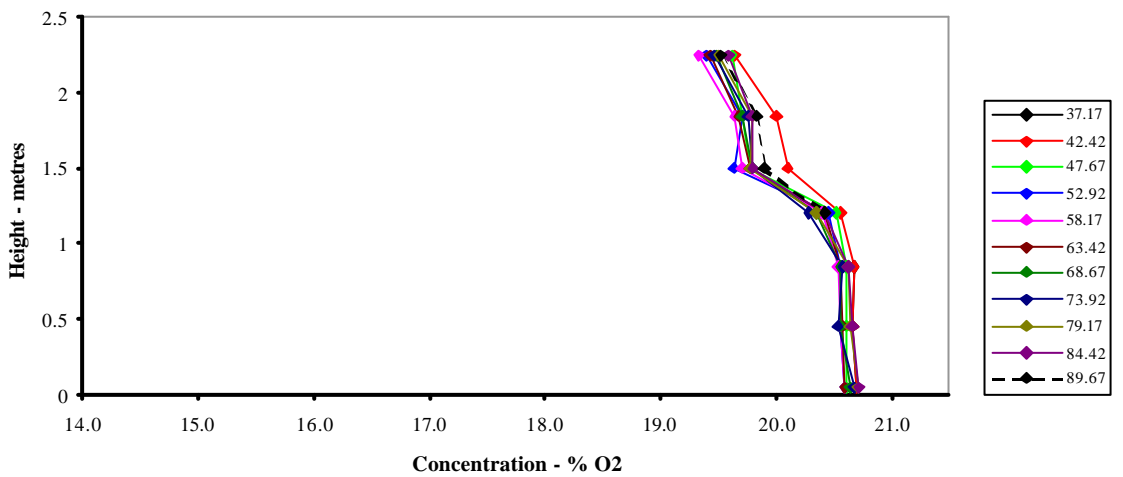
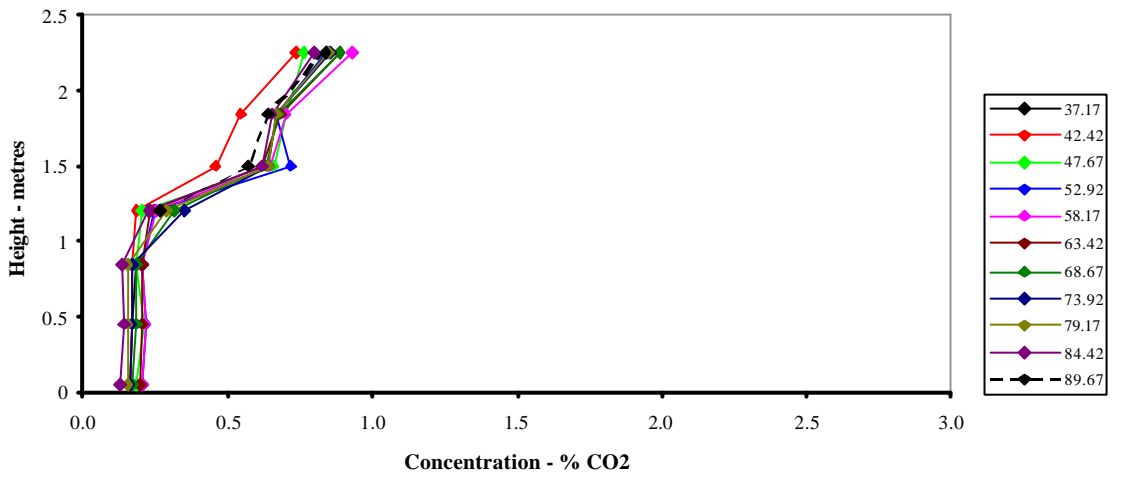
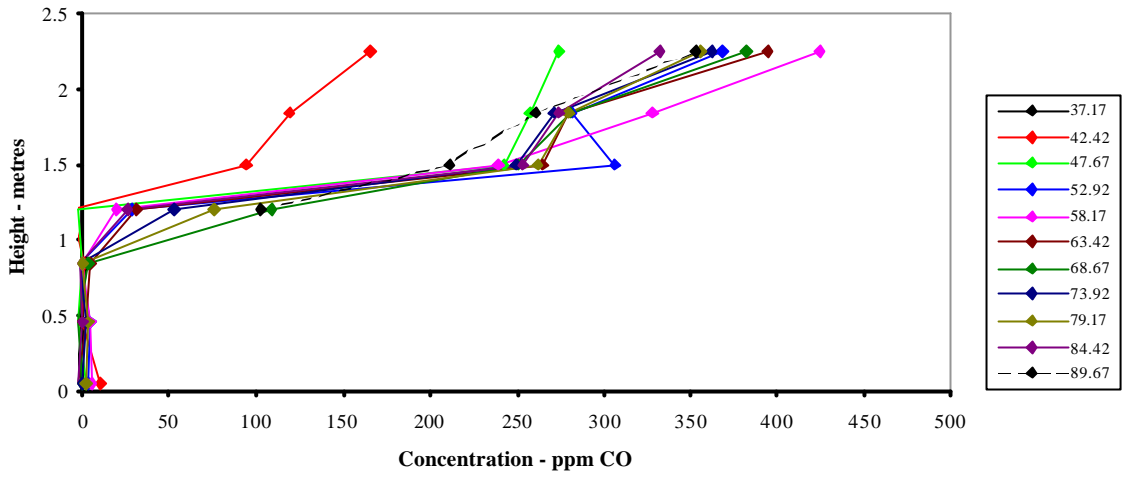


Figure A18(a)
Test 18. Concentration profiles in Room 1

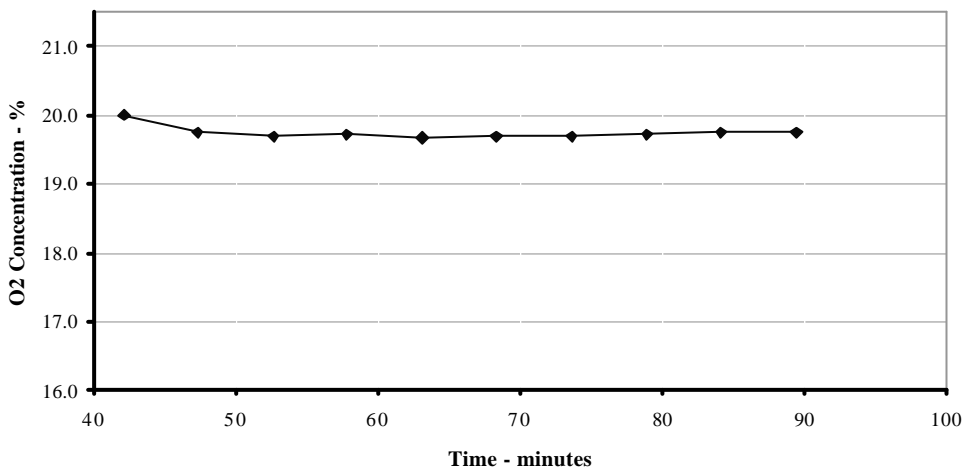
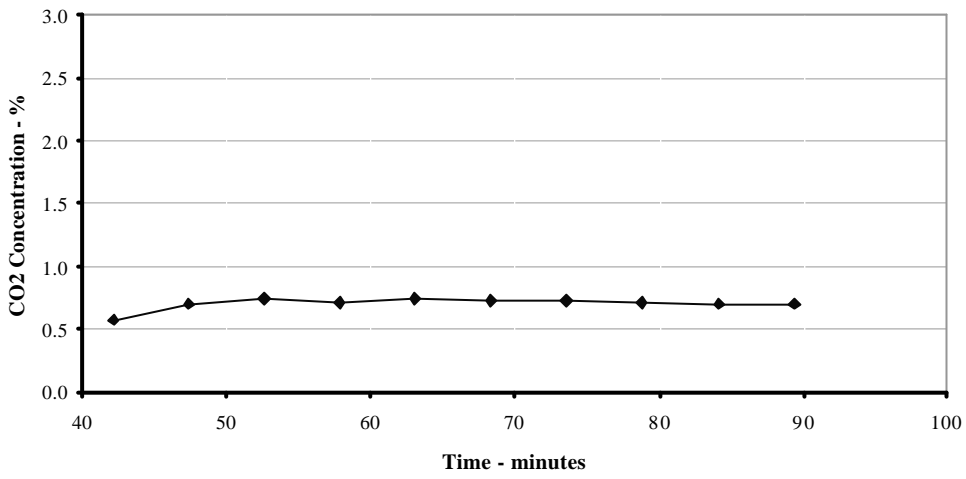
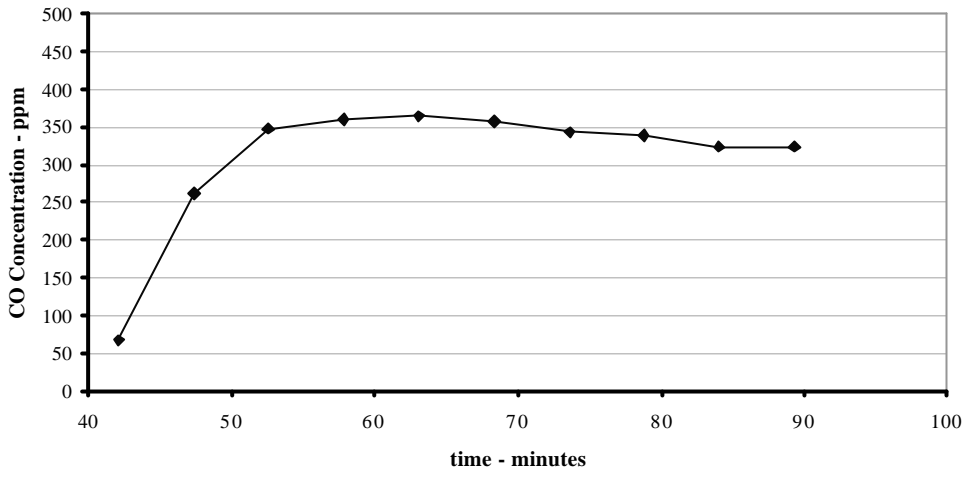


Figure A18(b)
Test 18. Concentration in the extract system

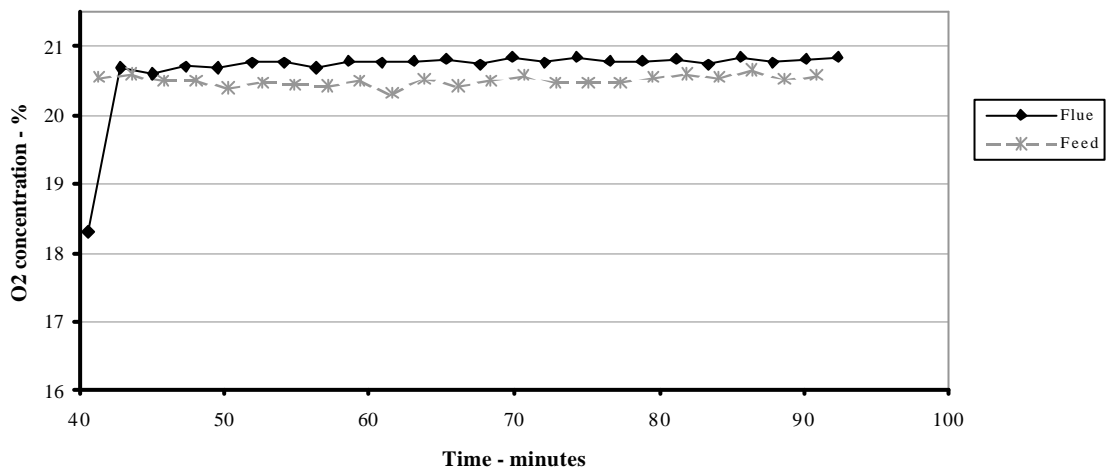
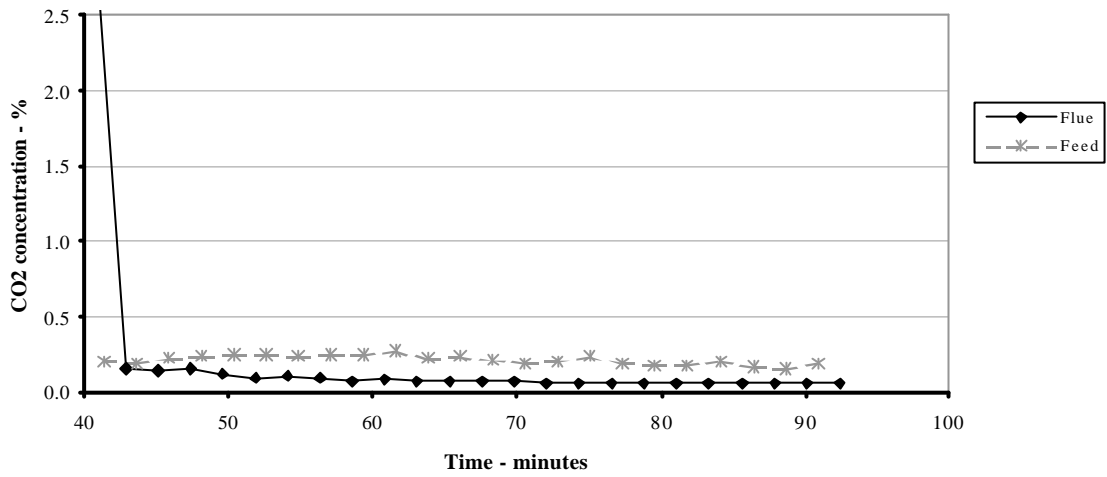
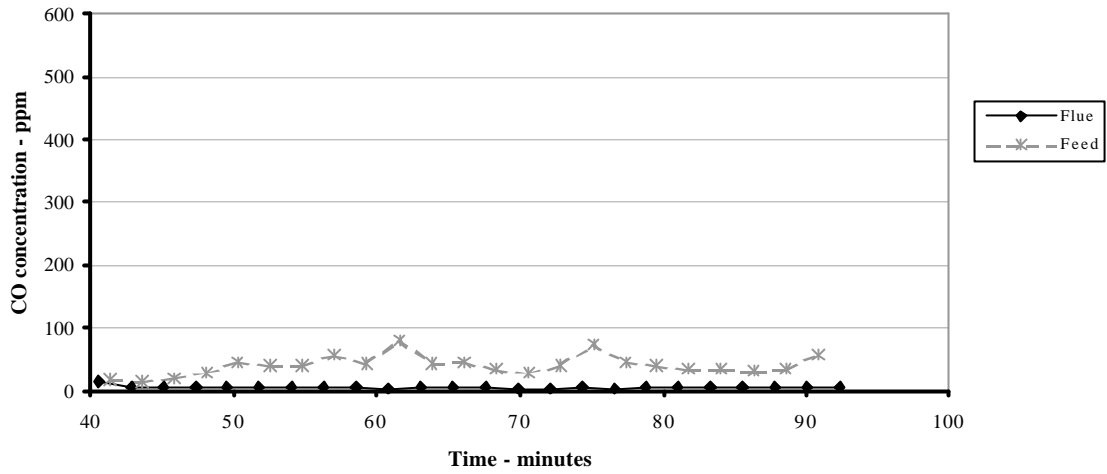


Figure A18(c)
Test 18. Concentration in the flue, and in the combustion air supply

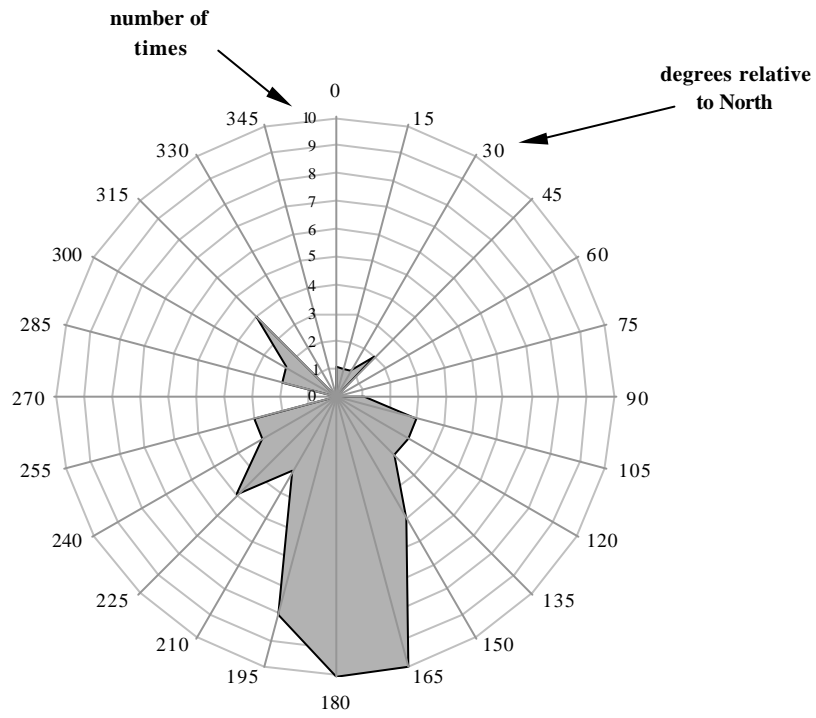
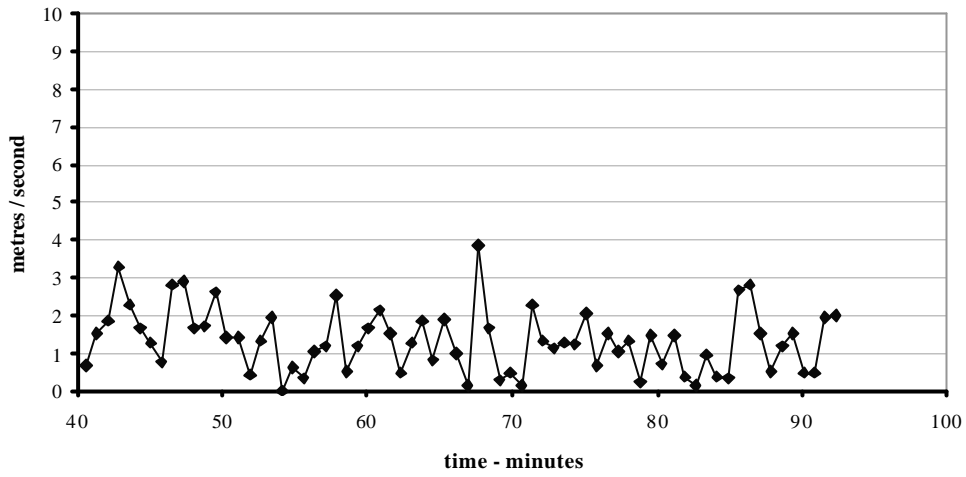


Figure A18(d)
Test 18. Wind speed and direction

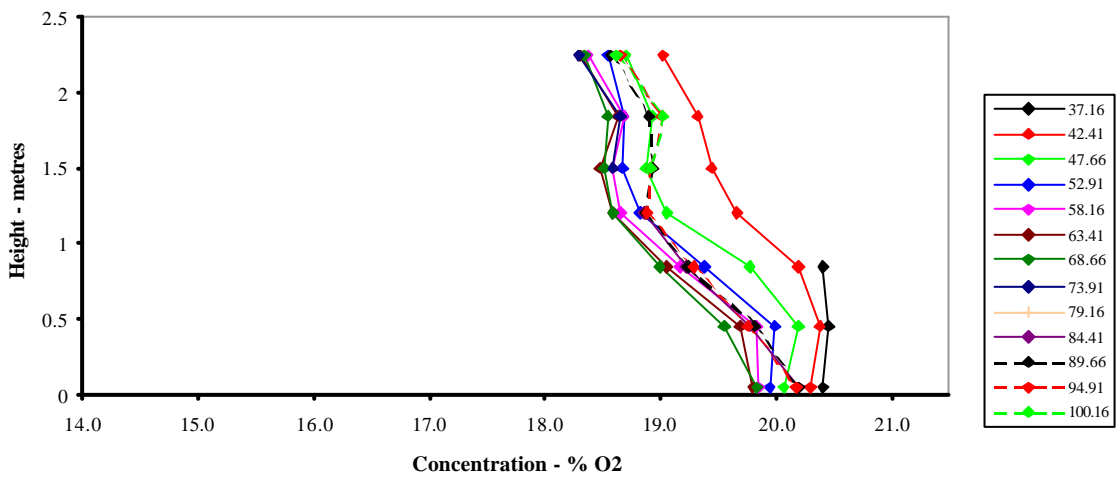
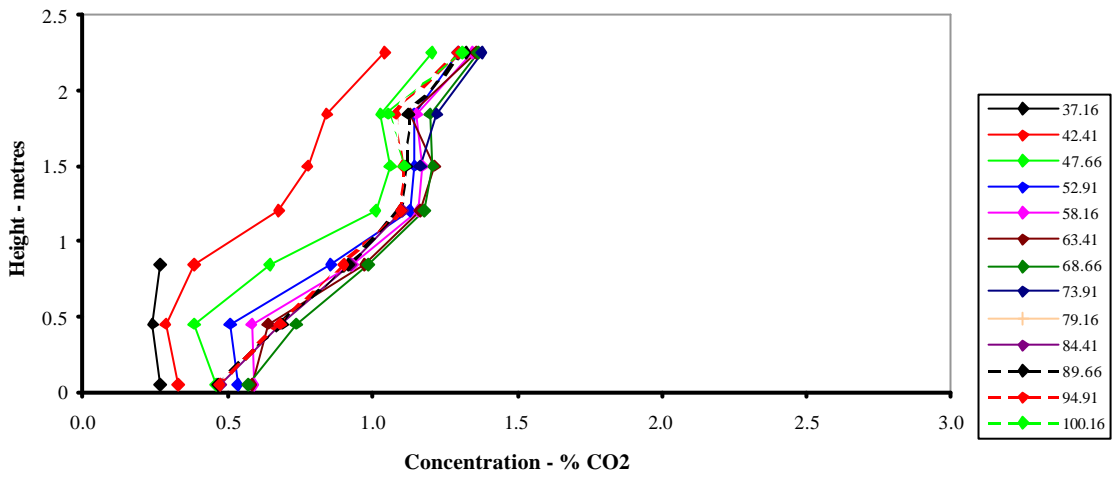
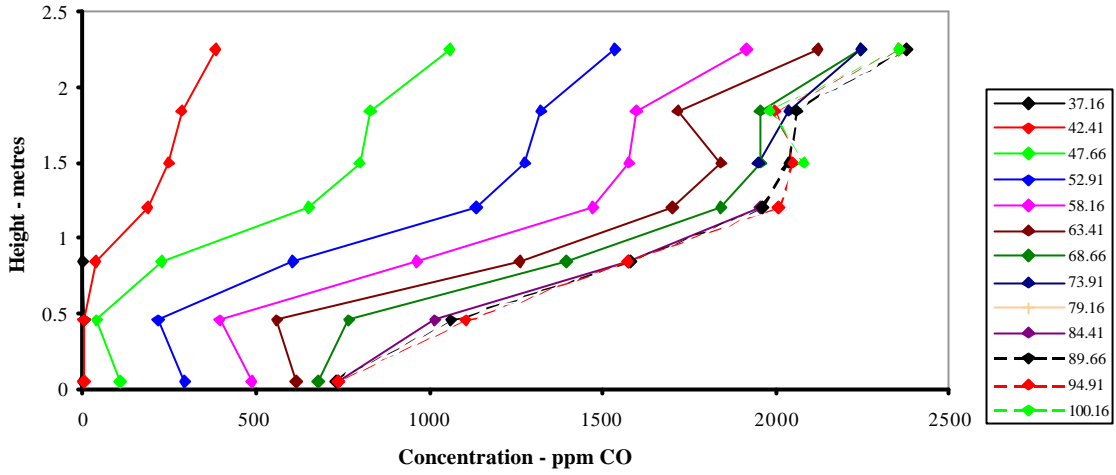


Figure A19(a)
Test 19. Concentration profiles in Room 1

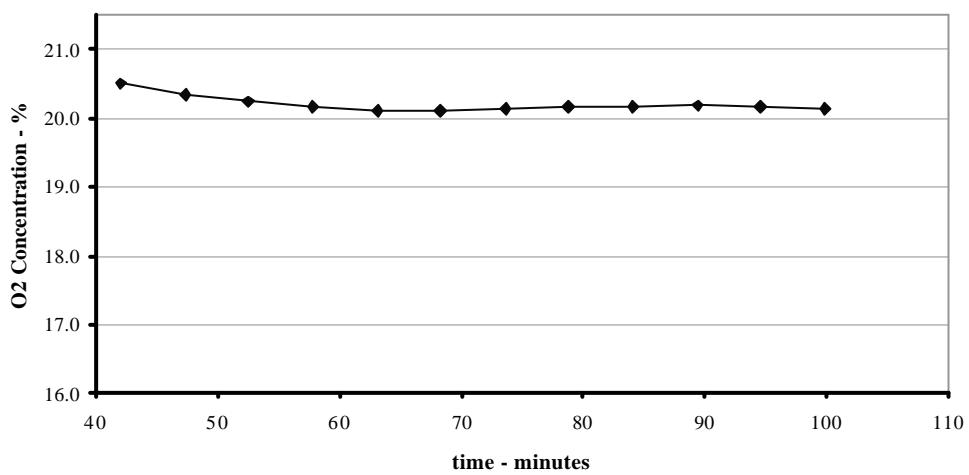
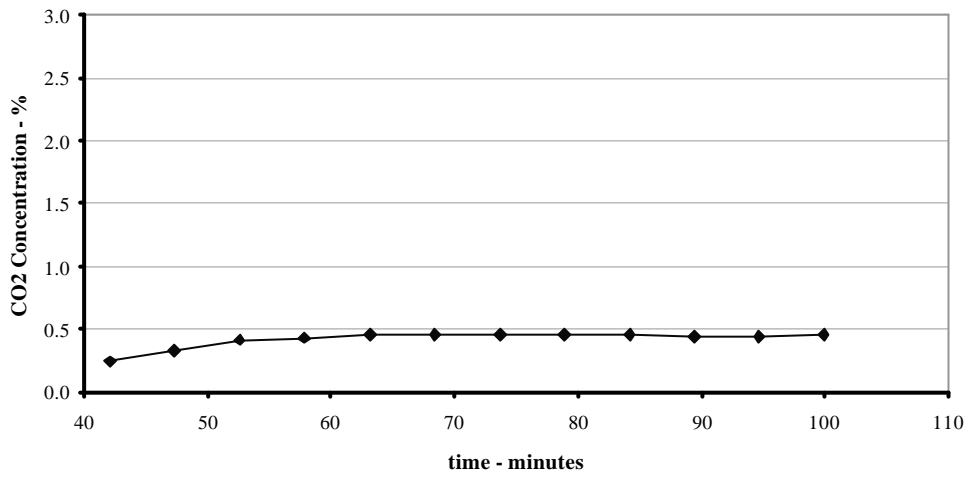
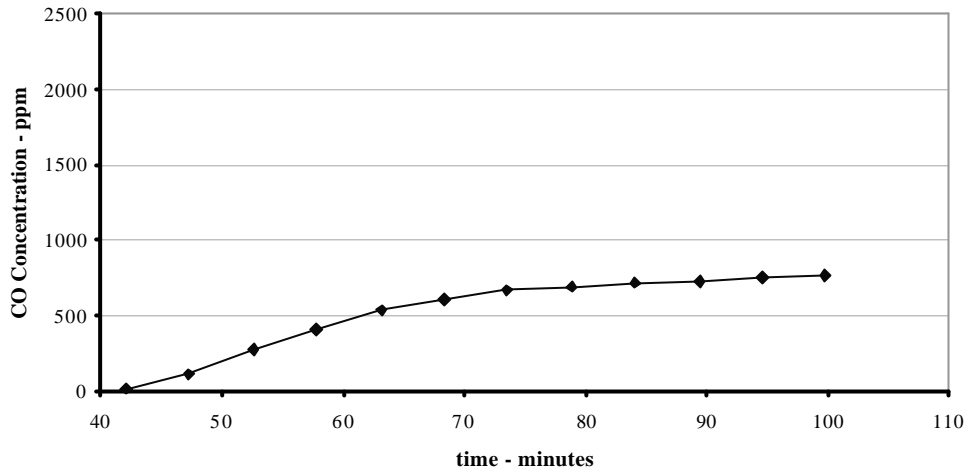


Figure A19(b)
Test 19. Concentration in the extract system

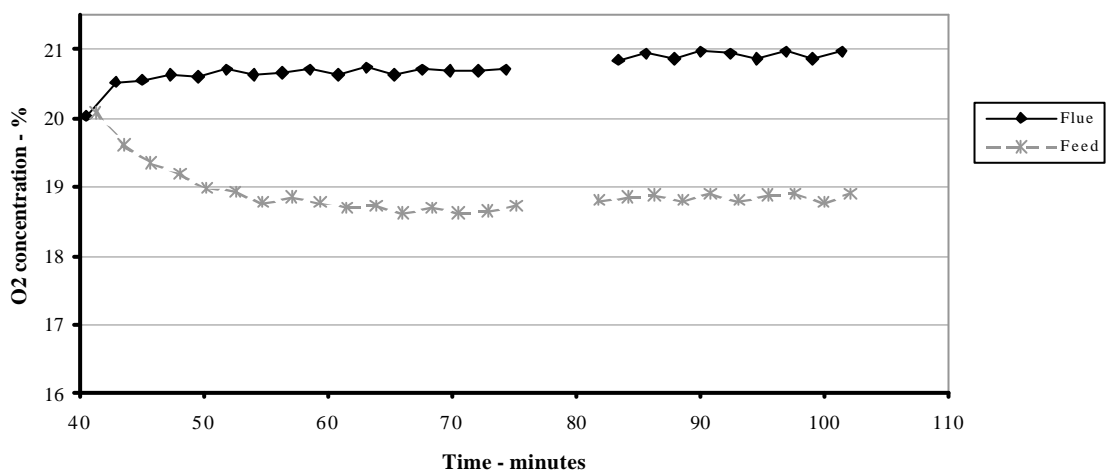
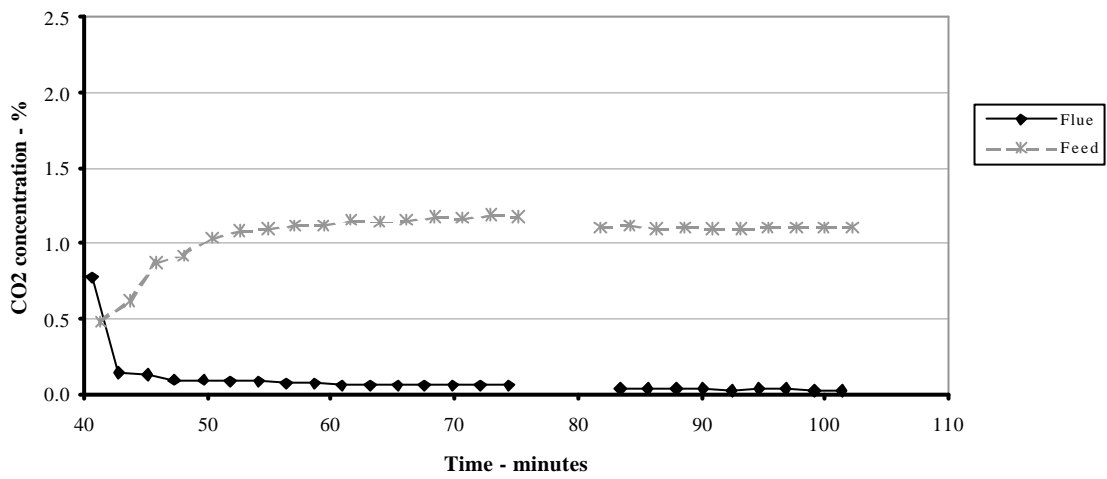
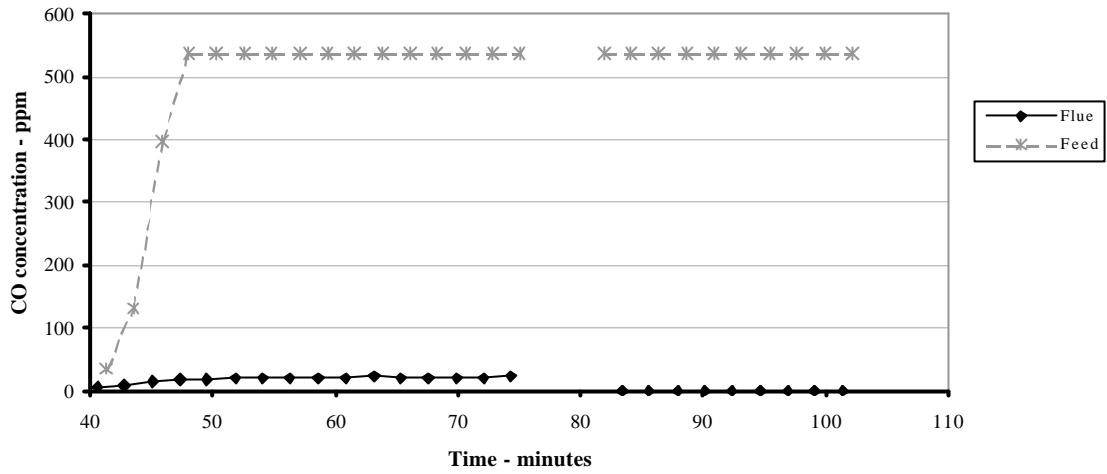


Figure A19(c)
Test 19. Concentration in the flue, and in the combustion air supply

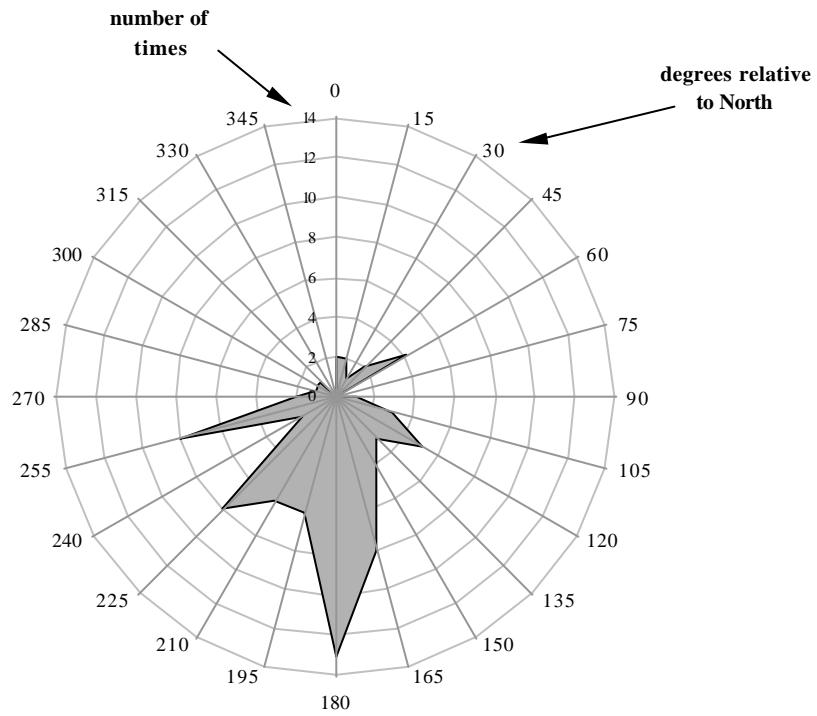
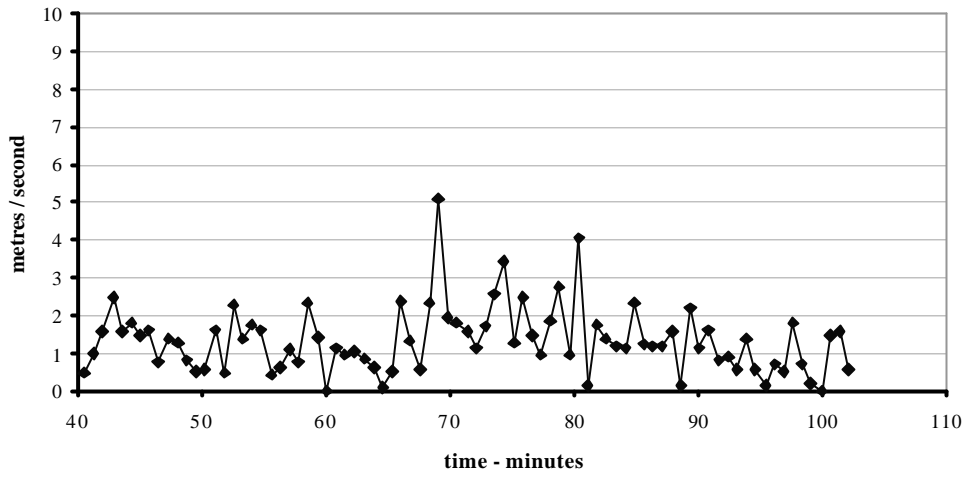


Figure A19(d)
Test 19. Wind speed and direction

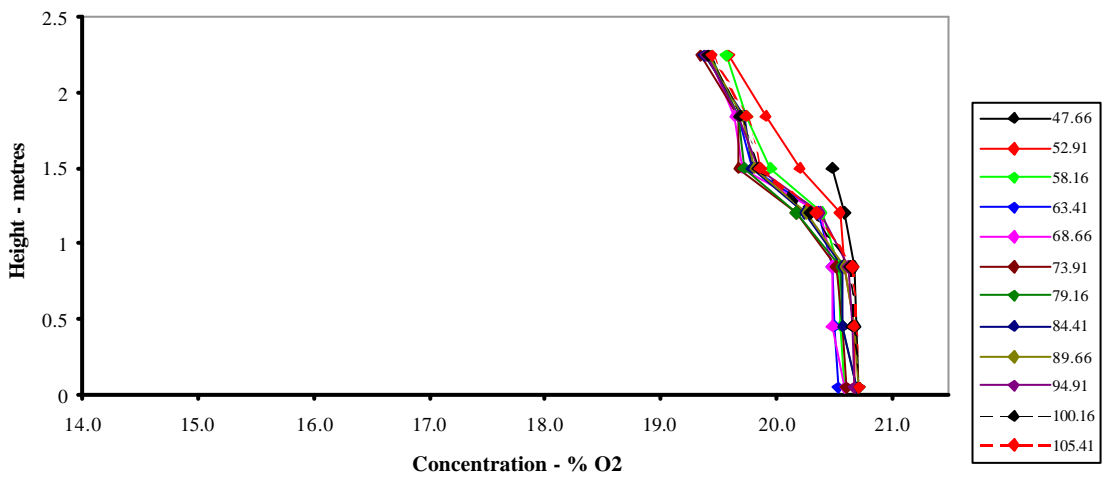
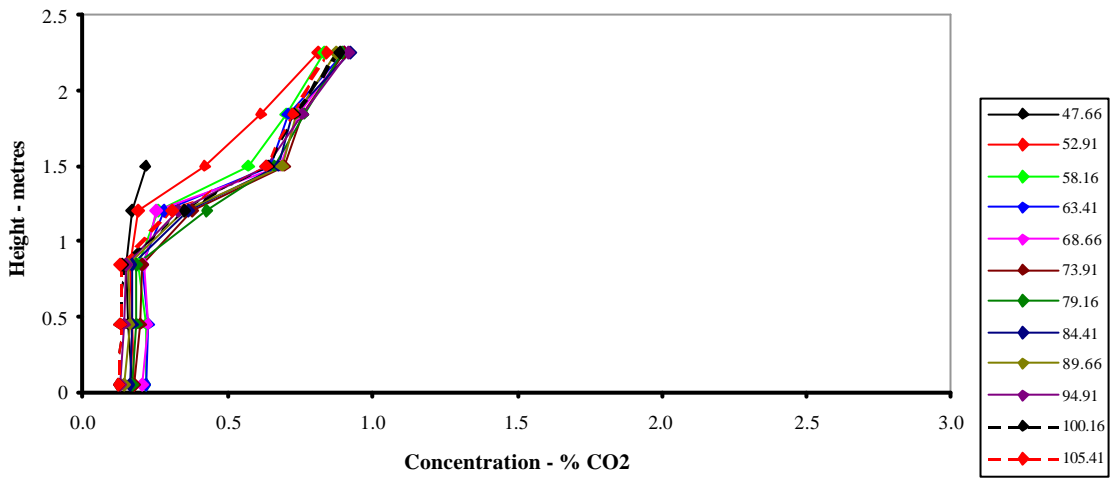
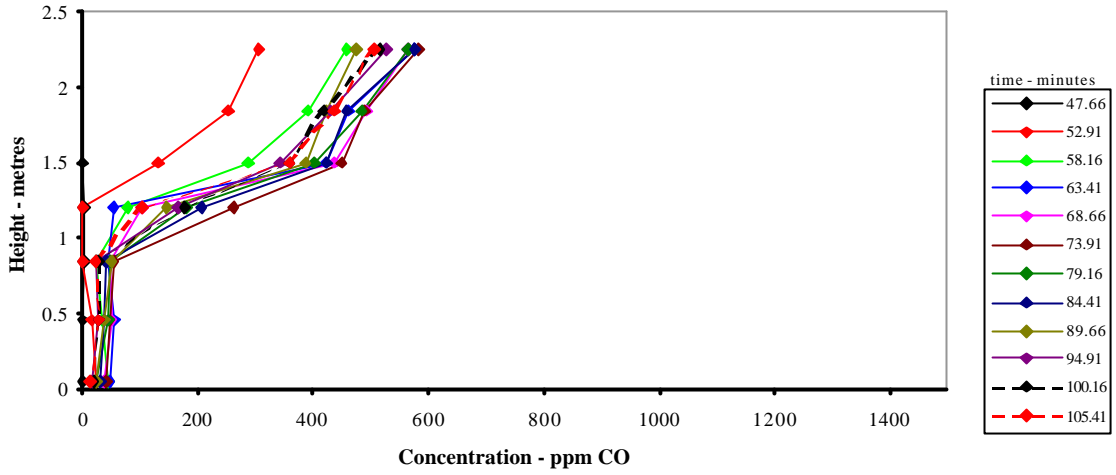


Figure A20(a)
Test 20. Concentration profiles in Room 1

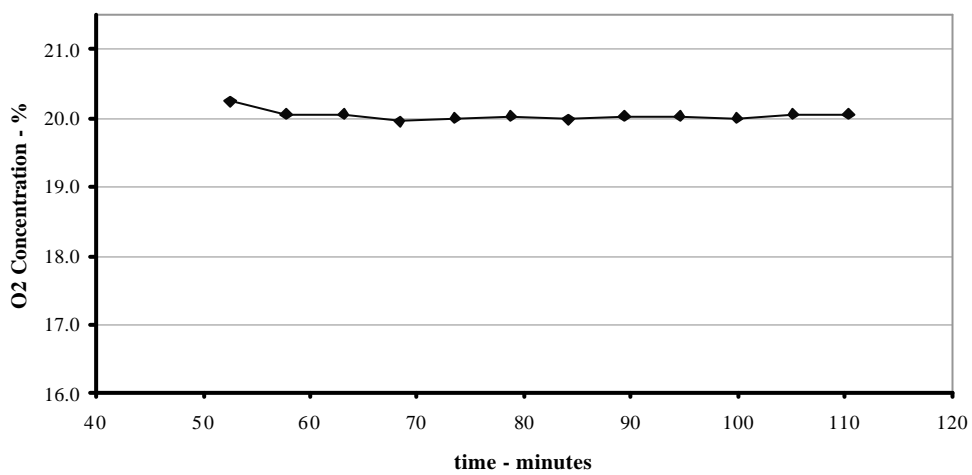
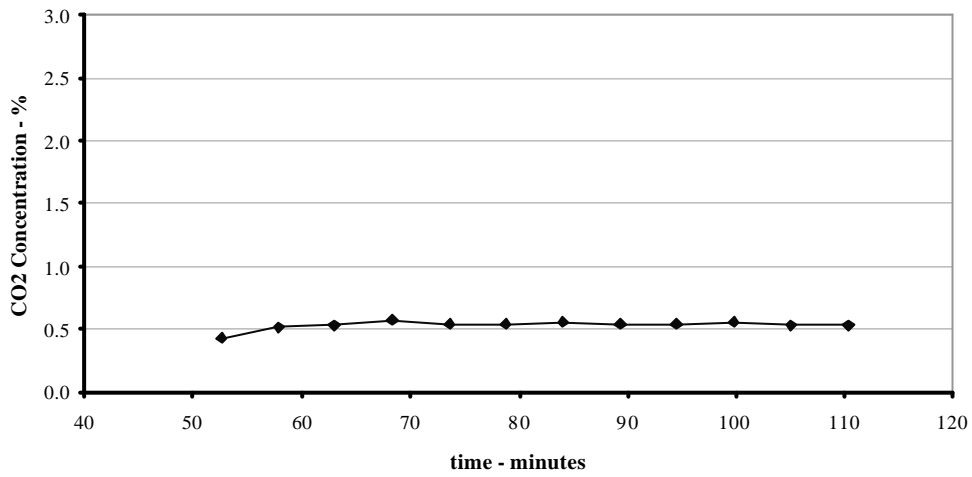
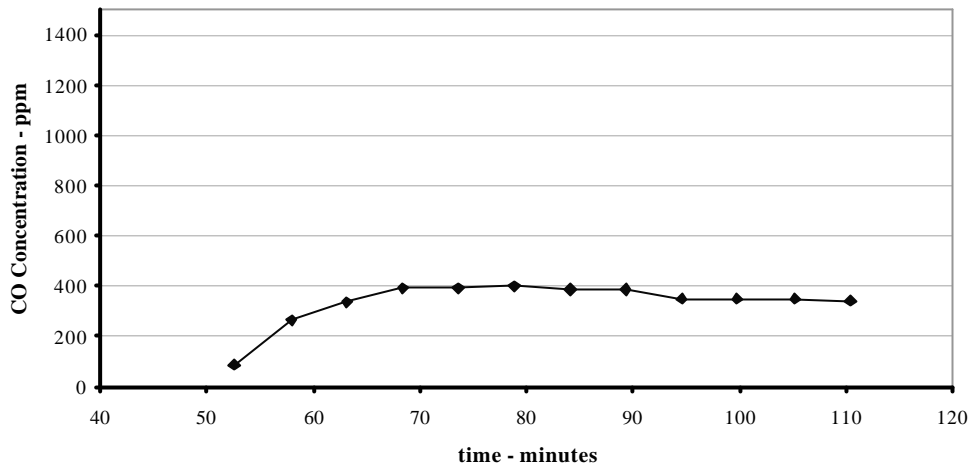


Figure A20(b)
Test 20. Concentration in the extract system

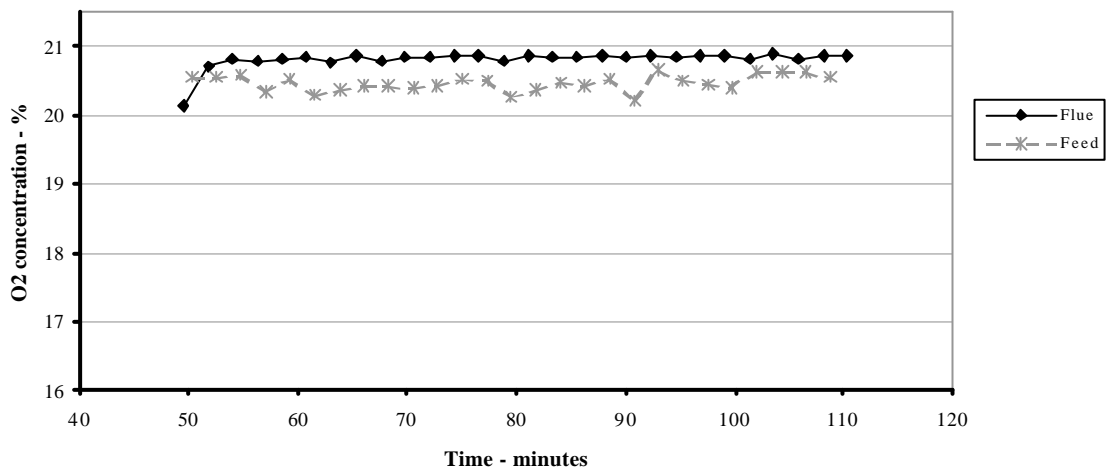
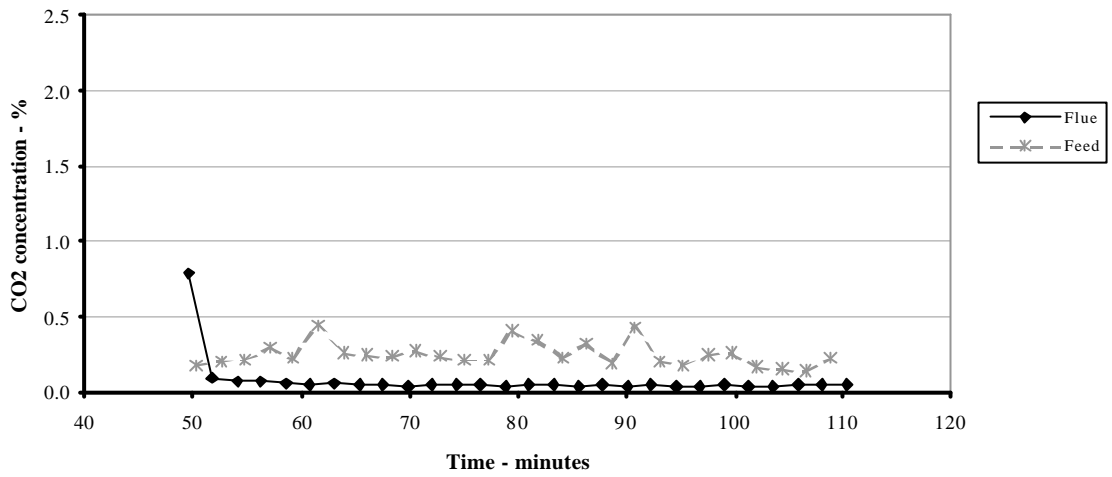
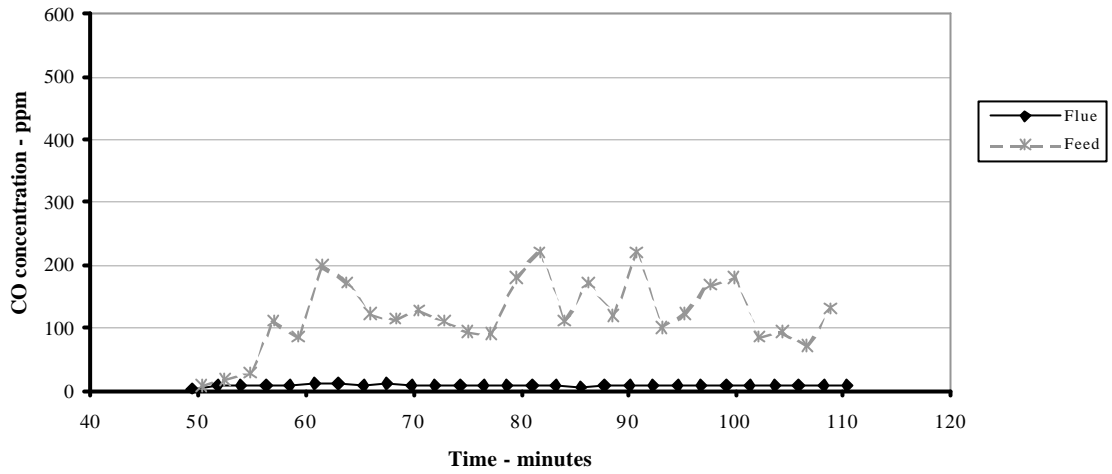


Figure A20(c)
Test 20. Concentration in the flue, and in the combustion air supply

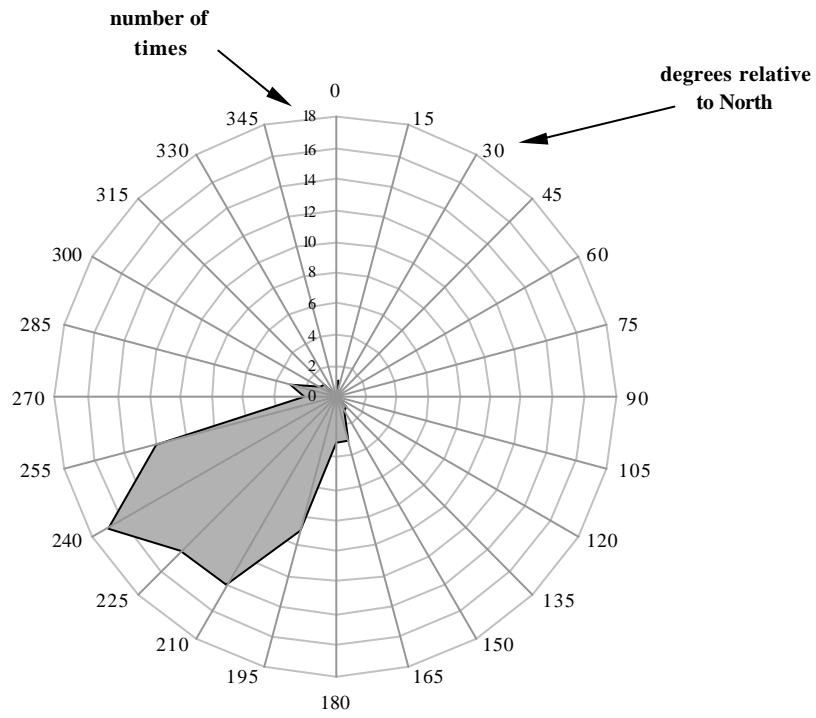
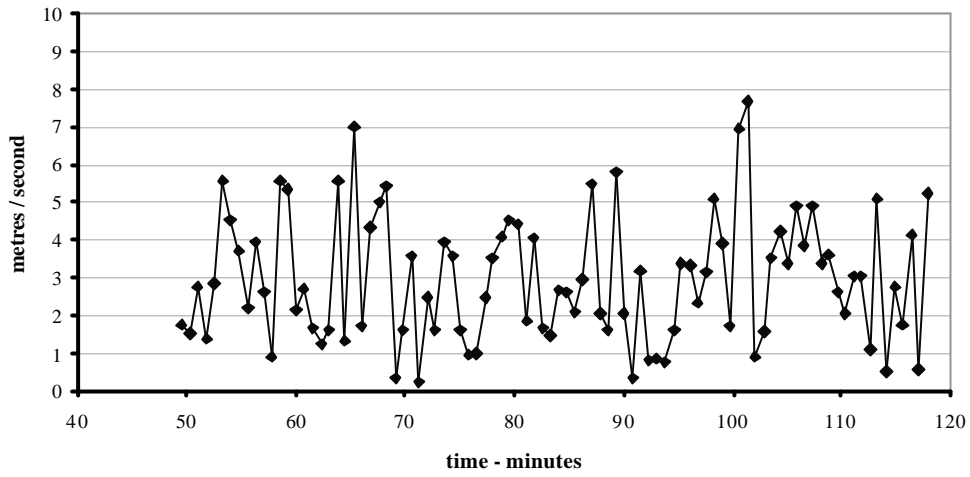


Figure A20(d)
Test 20. Wind speed and direction

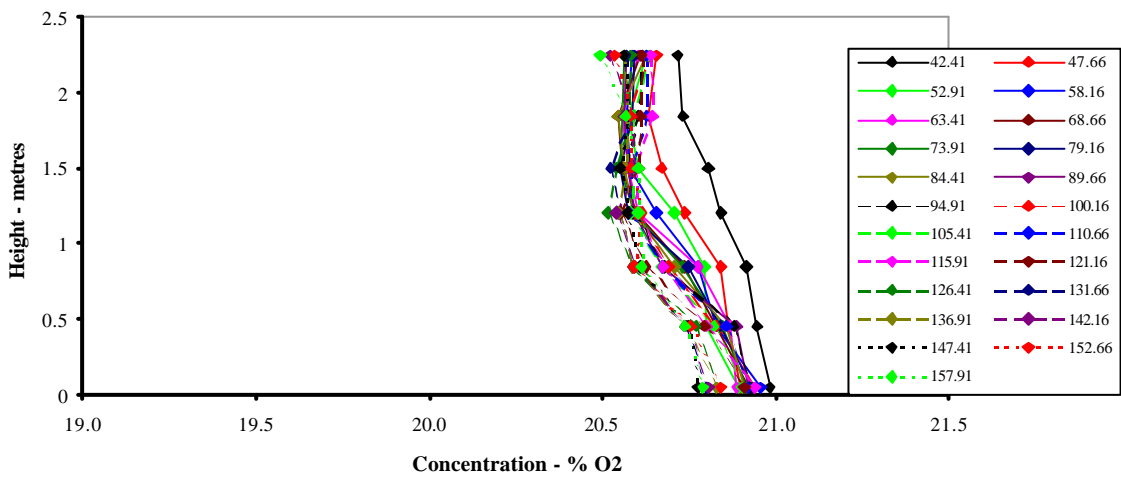
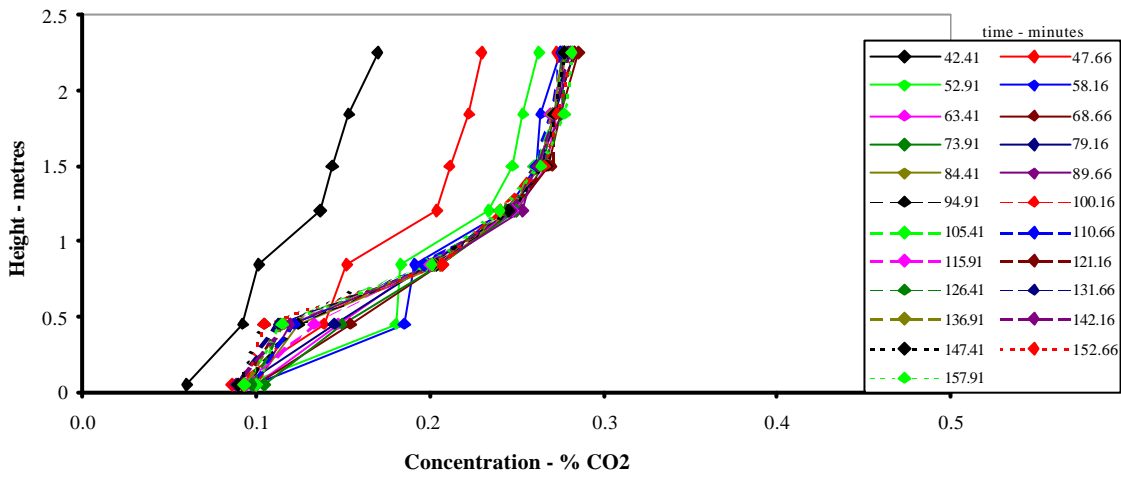
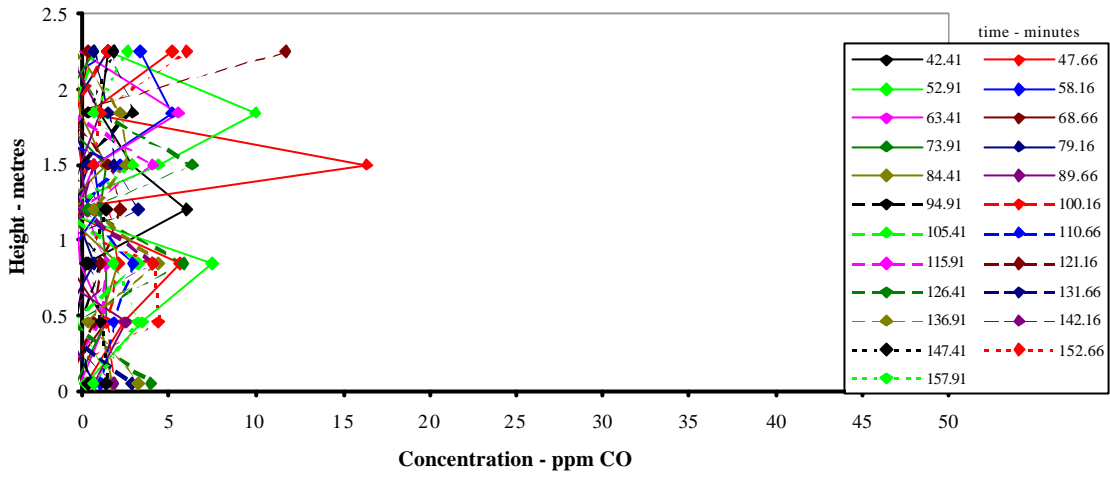


Figure A21(a)
Test 21, Concentration profiles in Room 1

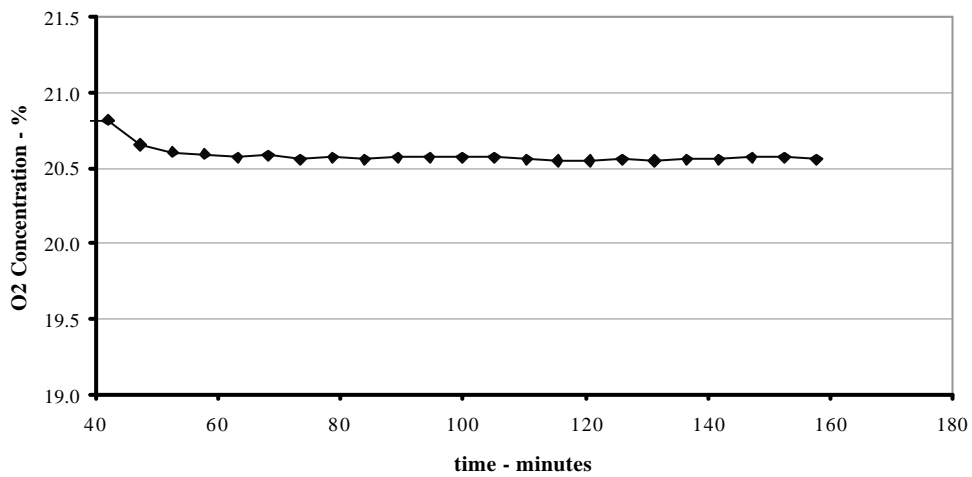
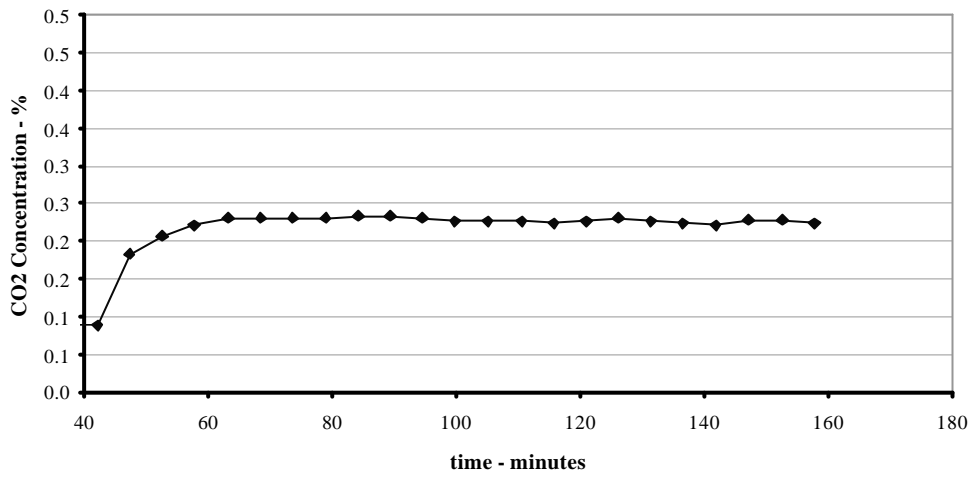
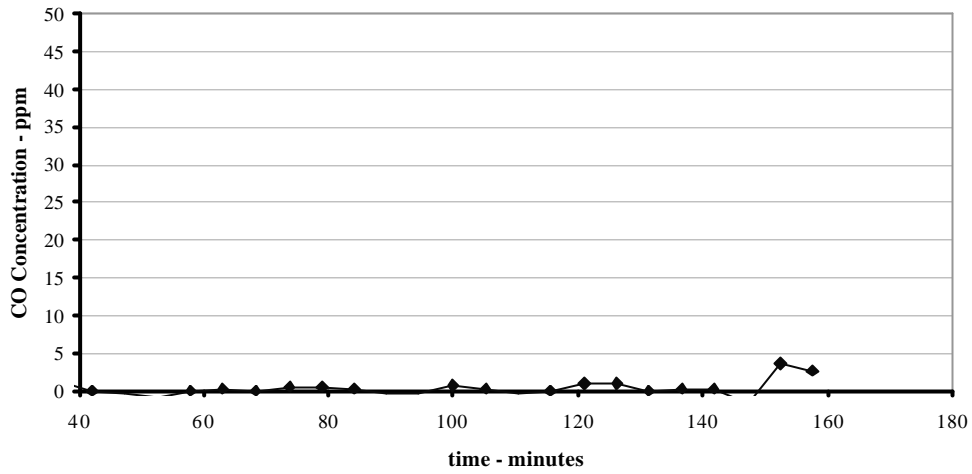


Figure A21(b)
Test 21. Concentration in the extract system

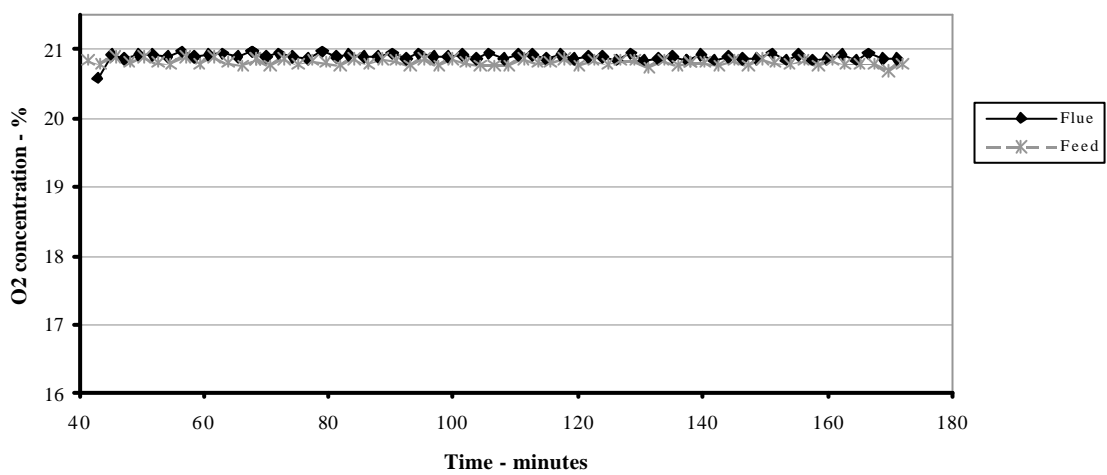
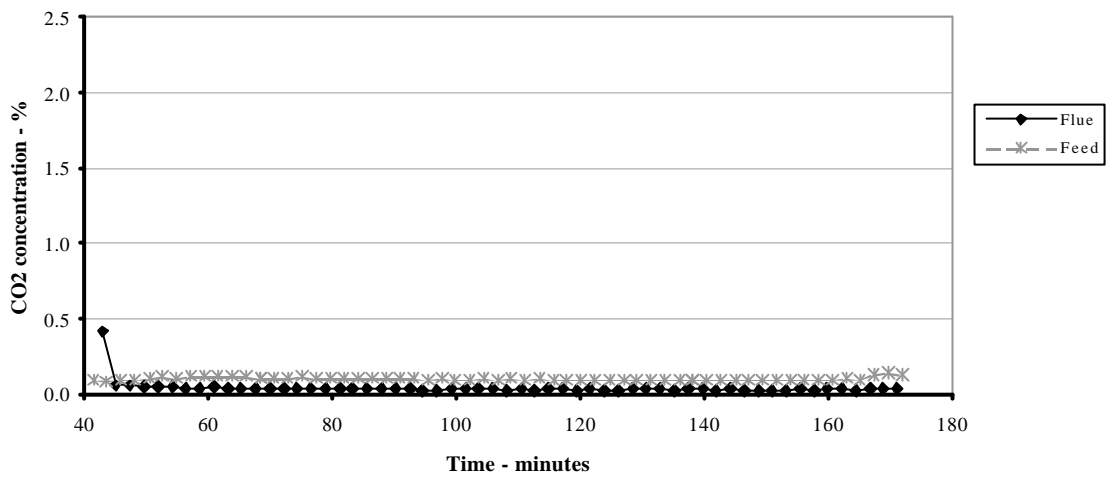
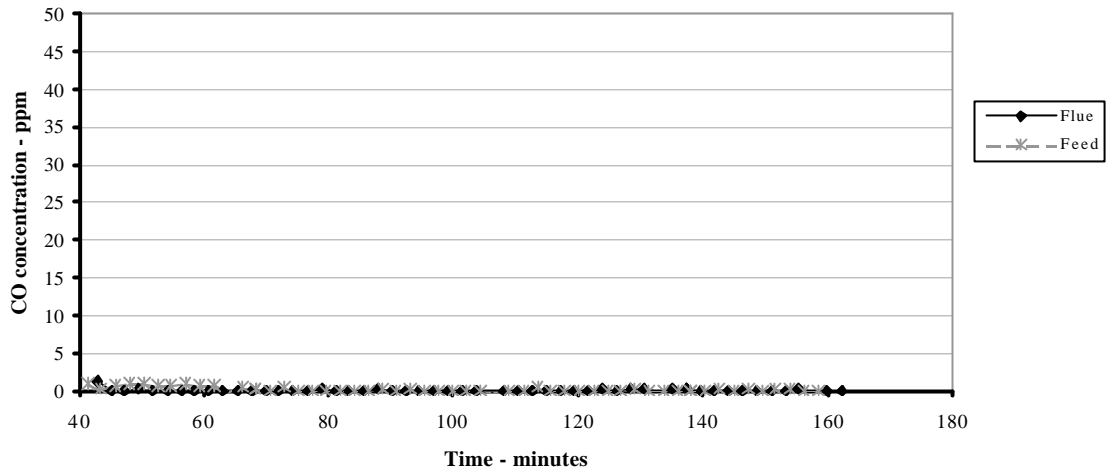


Figure A21(c)
Test 21. Concentration in the flue, and in the combustion air supply

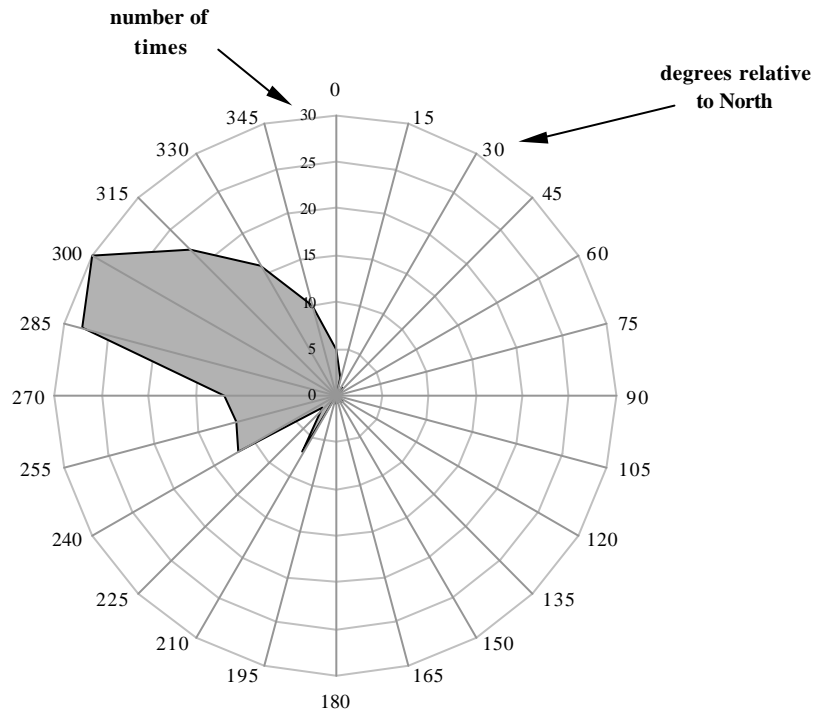
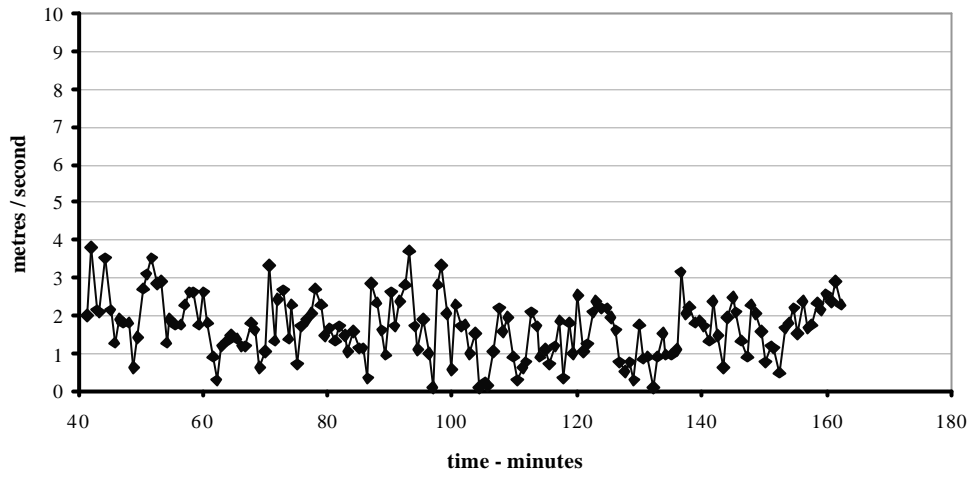


Figure A21(d)
Test 21. Wind speed and direction



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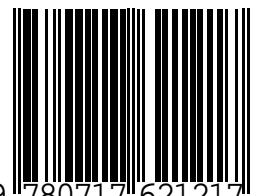
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