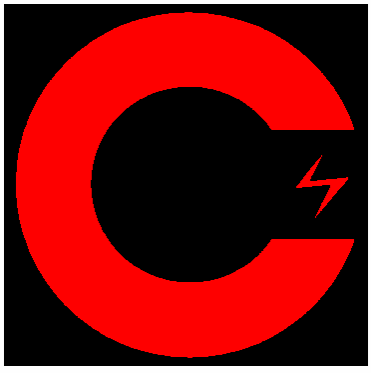
HFR400

Fast Response
Hydrocarbon Measurement System

User Manual

(version 3.5)



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EC Declaration of Conformity

We, CAMBUSTION LIMITED, declare that the products here listed meet the basic health and safety requirements of the relevant EC directives by design and by construction.

In the case that any product is modified without our approval, this declaration will be void.

Designation of products:

Fast Response Analyzers

Models:

HFR400 Fast FID
*f*NOx400 Fast NOx
LHC500 Line Heater Controller
HFR500 Fast FID
CLD500 Fast NOx
NDIR500 Fast CO&CO_2

Safety precautions and usage restrictions:

Refer to the manuals supplied with the equipment.
In all cases, take adequate safety precautions.

The products meet the requirements of the following directives:

EC Directive on Low voltage equipment (73/23/EEC)
EC Directive on Electromagnetic compatibility (89/336/EC)
EC Directive on Machinery (98/37/EC)

Applied harmonized standards:

EN50081-1
BS EN 61010-1

Cambridge, 19th April 2004

M. Peckham
Director of Products

T. Hands
Director of Research

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Warnings

The vacuum pump supplied with this system **MUST** be operated on a flat surface at a height at least 0.6metre (2 feet) lower than the MCU to which it is connected. (Cabinet mounted systems meet this criterion.) Failure to observe this may result in damage to the equipment should the vacuum pump fail.

The sampling heads become very hot under normal operating conditions. Before handling, they **MUST** be allowed to cool.

The HFR400 system operates using compressed pure hydrogen. To ensure continued safe operation:

1. Always turn off the gases at source when the system is not being used or is unattended

2. Leak check the MCU regularly (See Section 7.2.4)

3. Have the system serviced annually by Cambustion Ltd. (details of service contracts are available on request)

4. Carefully follow the setting-up procedures in Section 3.

5. The HFR400 control unit, cabinet and vacuum pump should be used in a well ventilated and should not be subjected to flammable atmospheres.

6. It is advised that any gas regulators employed should be serviced at a maximum interval of 5 years

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1 Background and Introduction

1.1 Physical origin of the FID signal

The basic physical phenomenon that is exploited in a Flame Ionisation Detector (FID) is that when a hydrocarbon is burnt, significant quantities of ions are formed. The number of ions produced is nearly proportional to the number of carbon atoms burnt in hydrocarbon (HC) form.

The physical explanation for this effect is not fully understood. The process of ion generation is certainly to do with a non-equilibrium effect called chemi-ionization, as opposed to thermal (equilibrium) ionisation, since the latter is responsible for negligible ionisation at normal flame temperatures. Appendix 0 contains further information regarding chemi-ionisation.

In flames not involving hydrocarbons, for example hydrogen and carbon monoxide flames, ion generation is limited to equilibrium values and is very small indeed. However, if a hydrocarbon sample is introduced into such a flame, significant ionisation occurs.

1.2 Conventional FID design

A practical implementation of these ideas is demonstrated in Figure 1.1, which shows a typical conventional FID arrangement. The flows of fuel gas, air and sample are carefully controlled typically via capillary tubes and pressure regulators. It is emphasised that these systems work extremely well but have the disadvantage that they necessarily have a poor frequency response, typically of the order of 1 second.

1.3 Cambustion Fast FID design

Figure 1.2 is a schematic diagram of the Cambustion Hydrocarbon Sampling Module (HSM). The essential difference from the conventional design is that the sample gas is mixed with the fuel gas at the nozzle exit. It is this design change which is the reason for the high frequency response, which in this system is limited only by dispersion effects within the sample tube and in the flame itself. Discussion of these effects is given in Sections 4 and 5, but it is evident that a short sample tube is desirable for good frequency response. For this reason the sample is drawn directly into the FID (rather than supplied via a pump as in conventional FID systems). Thus the flame chamber must be maintained at a pressure below that of the sample source and typically, the FID operates at below atmospheric pressure.

It is important to note that the since an FID produces an output which is proportional to the total mass flow of hydrocarbons, the instrument is only as accurate as the setting, or measurement, of the sample flow. In other words, in the Cambustion FID the interpretation of the absolute level of the FID output is dependent on the operator, since the operator sets the sample flow rate by, for example, control of the FID chamber vacuum.

Thus the design change over a conventional FID has produced important advantages, but also the significant disadvantage that the instrument cannot be merely switched on and the output interpreted as an HC concentration. However, by careful setting and calibration, as described in Sections 4 and 5, the accuracy of the device approaches that of conventional FID systems.

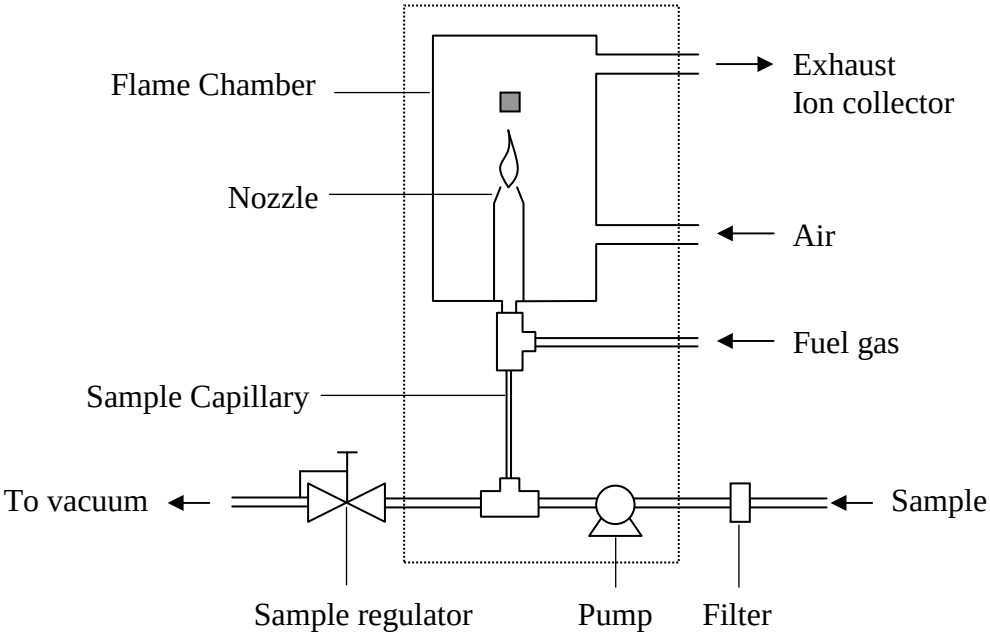

Figure 1.1 - Conventional FID

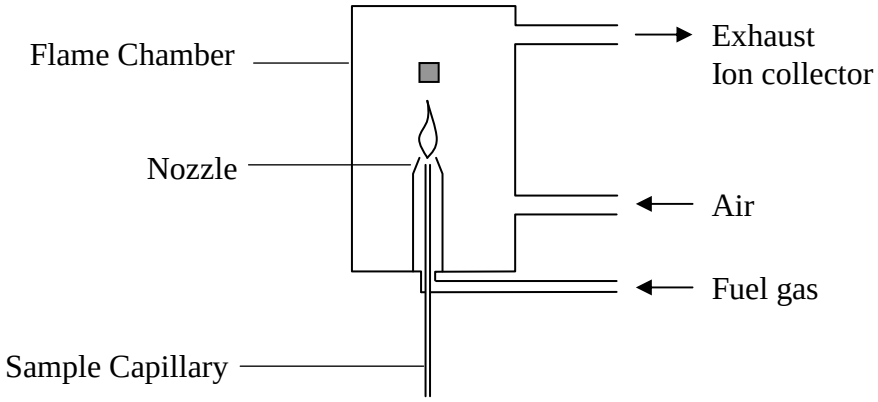

Figure 1.2 - Cambustion FID

2 Overview of the Cambustion FID

2.1 Introduction

The basic Cambustion HFR400 system consists of a Hydrocarbon Sampling Module (HSM) and a gas handling and electronics subsystem, the Main Control Unit (MCU). The sampling head is a small, light, and portable unit, so that the FID flame chamber can be very close to the hydrocarbon source, allowing short sample line lengths and very high frequency response. It is connected via a conduit to the MCU. Figure 2.1 shows a possible system for sampling from constant pressure (usually atmospheric) environments. Figure 2.2 shows a system equipped with a constant pressure system to be used when sampling from areas of fluctuating pressure (typical in internal combustion engines).

2.2 Sampling Head (HSM)

NOTE: The HSM becomes very hot during operation. Please be careful when handling. The collector inside the HSM is at 180V and could be lethal. Please consult Section 7 'Maintenance' before dismantling.

Figure 2.3 shows the sampling head in detail. It consists of a burner assembly (1), which is supplied with hydrogen fuel gas via (13), air via (11), and sample via (18). The vacuum in the FID chamber, which causes the sample flow, is achieved by connecting the FID chamber to the vacuum supply via a restrictor (10). This in itself is not sufficient to accurately control the vacuum pressure in the FID. This is achieved by a bleed flow of air (9), which originates from a vacuum controller in the Main Control Unit (MCU).

The flame is initiated by means of the glow plug (5), and the flame status is determined by monitoring the chamber temperature via the thermocouple (6).

Negative ions (mostly electrons) generated in the flame (2) are collected at the electrode (3) which is maintained at 180V (+ve) with respect to the body of the FID. The collector electrode is mounted inside an insulator (7).

The vacuum in the CP chamber (if fitted) is derived and controlled in the same way as the FID vacuum, by means of a restrictor communicating with the vacuum line, and a second bleed flow of air originating from a vacuum controller (12).

2.3 MCU - Gas Handling Sub-system

This unit supplies the FID with its gas and vacuum requirements and includes automatic gas shut-off in the case of flameout.

Figure 2.4 shows the front panel layout. The fuel gas and air supplies to the unit are attached at (1) and (2) respectively. A vacuum line is attached at (3). The gas connections to the Hydrocarbon Sampling Module (HSM) are via miniature (1/8") snap connectors for Hydrogen (4) and air (5) and 6mm snap connectors for Vacuum (6), FID bleed (7), and CP bleed (8).

A start switch on the electronics sub-system (see next section) allows the fuel and air supplies to reach the FID if it is cold. This feature is necessary to allow lighting while ensuring automatic shut – off in the event of flame out. Pressure regulators upstream of flow capillaries determine the flow rates of fuel and air.

The FID vacuum is controlled by the FID vacuum regulator (9). In fact it controls the difference of pressure across the FID tube (ΔP), so that if a CP chamber is fitted, it is the difference between FID and CP pressures that is controlled.

If a constant pressure (CP) sampling system is fitted, the CP chamber pressure is adjusted by means of the CP Adjust controller (10) on the MCU.

Reference may also be made to Appendix E in which full details of the gas handling system are given.

2.4 MCU - Electronics Sub-system

WARNING: Parts of the MCU electronics sub-system are at lethal voltages

The Electronics Sub-system performs three functions

1. Amplification of the FID signal.

2. Monitoring of the temperature and pressures in the HSM.

3. Operation of the glow plug starter and an automatic shutdown system.

2.4.1 Amplification

Fig 2.3 shows the front panel controls on the electronics sub-system. The controls available to the user are:

1. Gain control setting (15)

2. Span control (16)

3. Offset control (17)

These enable the conversion factor between FID current and output voltage to be set. The gain control allows multiples of 1, 2, 5, 10, 20, 50, 100, 200, 500. The span and offset controls are used in the conventional way to provide a convenient output level for standard calibration gas, and at the same time remove zero offsets. The output signal appears at the BNC socket (18). The output impedance of the instrument is less than 100Ω.

Full details of the FID amplifier are given in Appendix C. It is important that any instrument connected to the output from the HFR400 will not be damaged by voltages in the range -12V to +12V.

2.4.2 Pressure and Temperature Measurement

The electronics unit contains 4 digital panel meters. There are 2 meters for each channel and switches (19) and (20) allow any 2 of the following parameters to be selected simultaneously.

ΔP FID—pressure difference across the sample (FID) tube (mmHg).

CP VAC—gauge pressure in the CP chamber (mmHg)

TEMP—Combustion exhaust temperature in the HSM (°C)

OUTPUT—FID output level (V).

2.4.3 FID Ignition Controls

Figure 2.4 shows the FID start controls. The Off/On/Start switch (21) is used to override the automatic cutout. When the unit is switched on and the switch is held in the start position, the status LED (22) will show red indicating that the chamber temperature is below 100°C, the glow plug is functioning and the air and fuel gas solenoid valves are open. This action also causes the FID vacuum to be momentarily vented to atmosphere to facilitate lighting at low FID pressures. If the switch is released at this point the gas flows will be cut off. Assuming the FID lights correctly, the temperature will rise, as indicated by the digital panel meter in `temperature' mode. When it exceeds 100±5°C, the status LED will change to yellow and if the start switch is released the LED will change to green, and the fuel gas and air supply will be maintained.

Status Indicator Summary

Unlit Gas shut off, power off and/or temperature below 100°C

Red Start selected, gas on, temperature below 100°C

Yellow Start selected, gas on, temperature above 100°C

Green Normal function, gas on, and temperature above 100°C

Note that no gas will flow until the electrical connection to the sampling head has been made at (23).

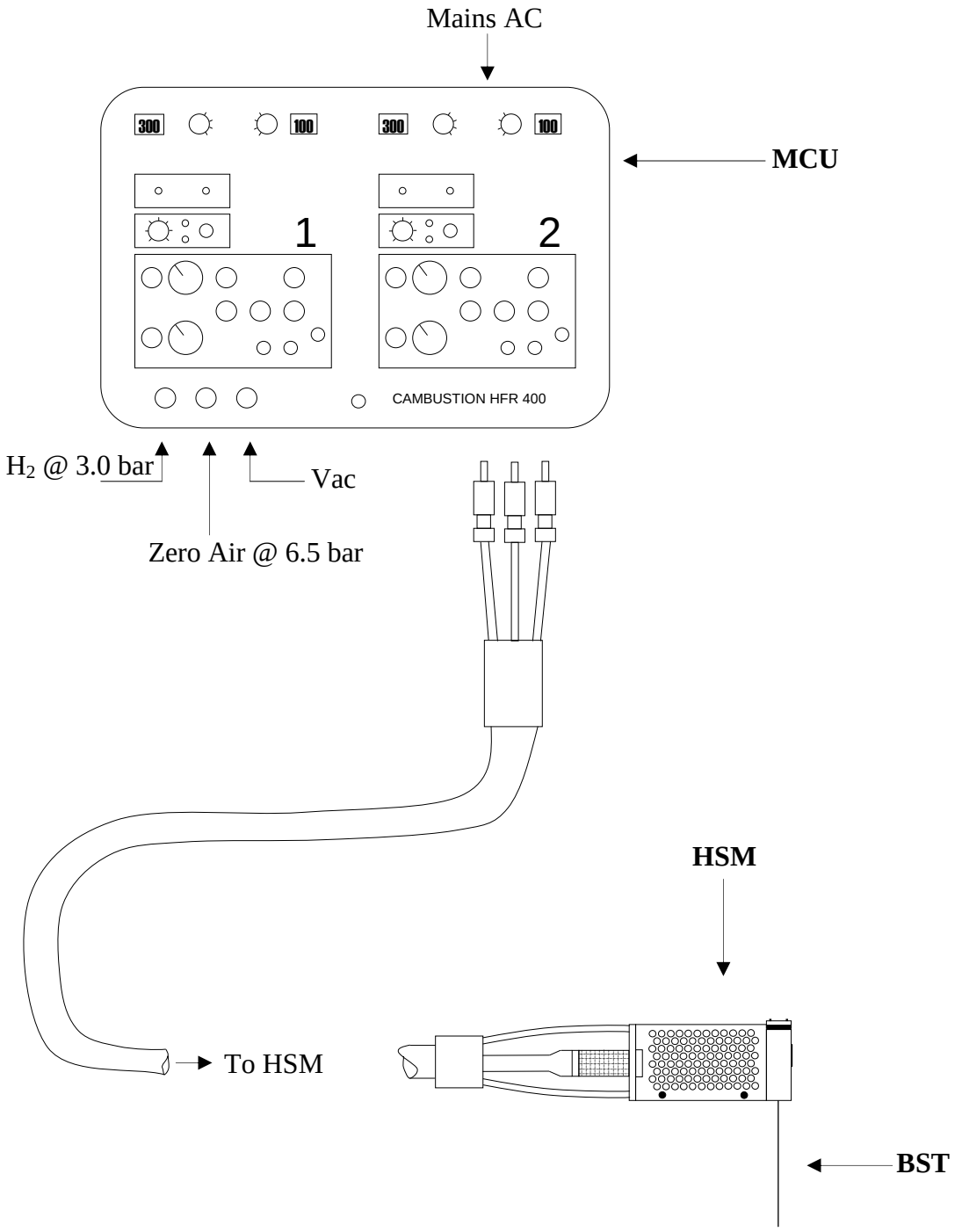

Figure 2.1- Cambustion HFR400 system for atmospheric sampling

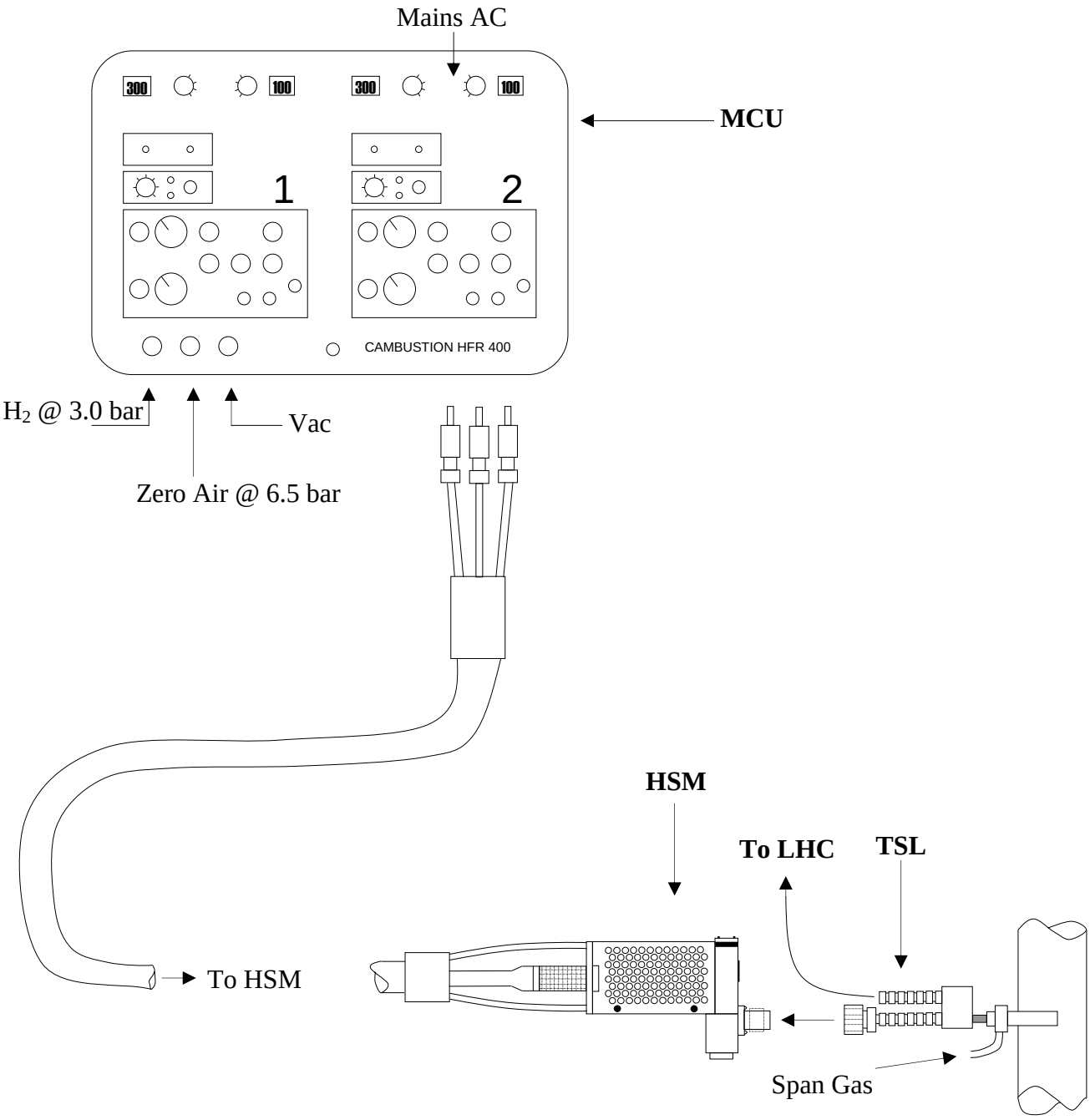

Figure 2.2– Cambustion HFR400 system with CP system

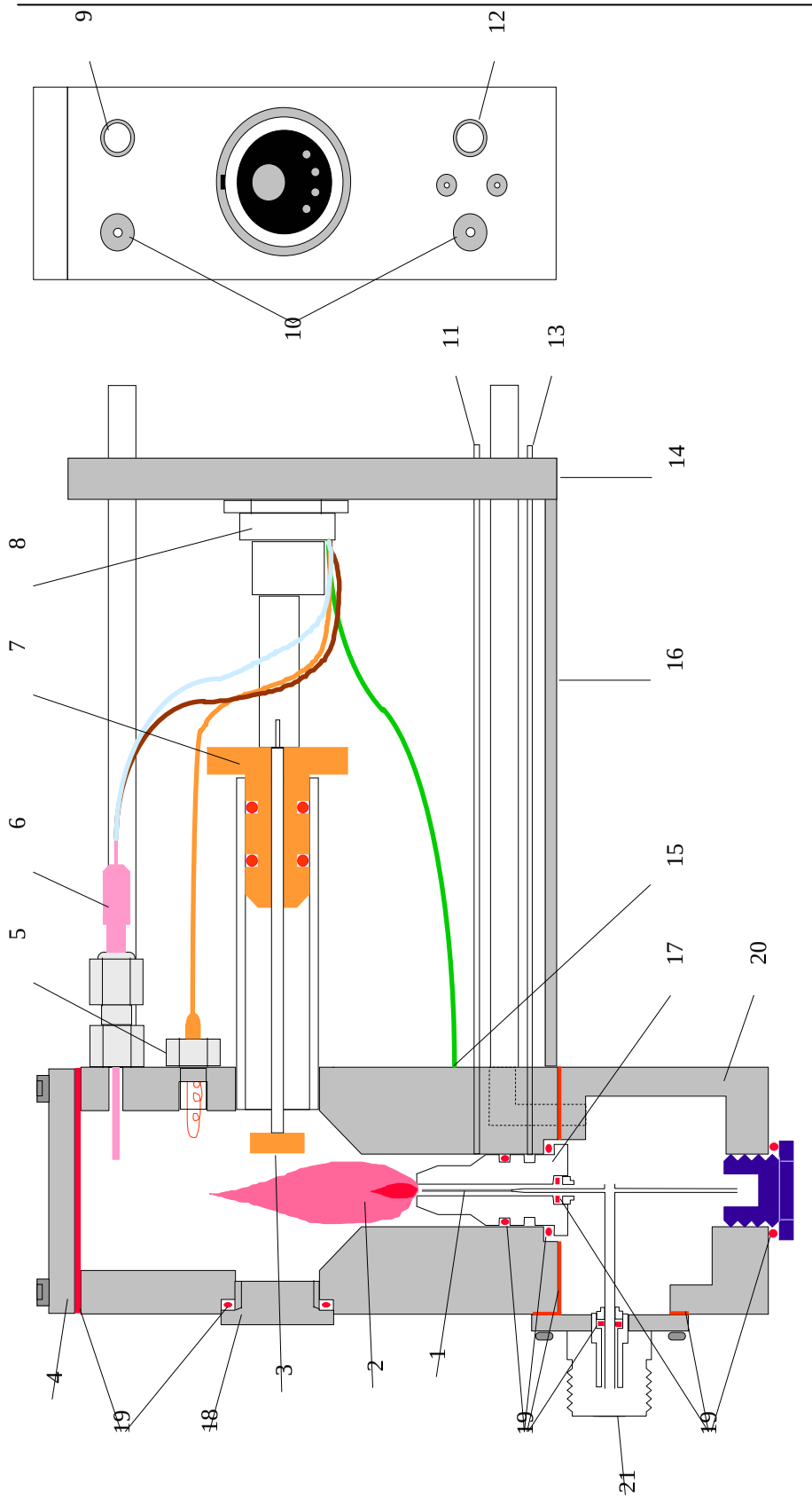

Figure 2.3– Cross Section through HSM

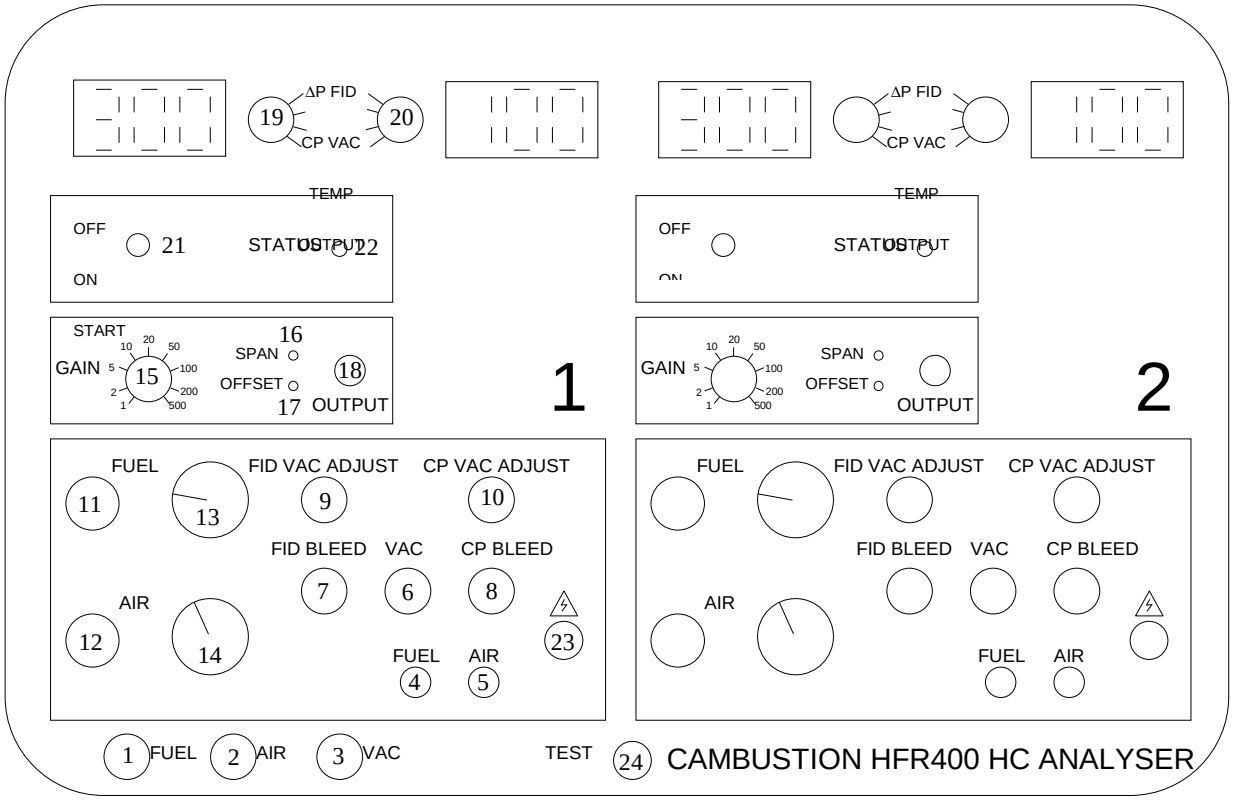

Figure 2.4 - MCU Front panel

3 Setting-Up

3.1 Unpacking

Carefully unpack the unit. If any damage has occurred during transit contact Cambustion immediately.

The boxes should contain

1 MCU (Main Control Unit)

1 DCS (Dynamic Calibration Unit)

1 LHC (Line Heater Controller Unit)

1 or 2 HSM(s) (Hydrocarbon Sensor Module(s)) with mounting tripod(s)

2 or 3 TSL-Hs (Heated Sample Lines)

1 Tool Kit

1 Vacuum Pump and 4m of 6mm black vacuum tubing with snap connector, 1 Litre of vacuum pump oil and operators guide

1 Quick User Guide

1 User Manual (including SATFLAP software)

1 Cabinet (if ordered)

IMPORTANT: It is essential that the vacuum pump is filled with oil prior to starting or serious damage will result. Always check the oil level before operation. See the vacuum pump operators' guide for details.

The exhaust of the vacuum pump is slightly contaminated with oil and it is advisable to arrange for the exhaust to be ducted away and/or filtered. Cambustion can provide a suitable filter. No additional volumes should be included in the vacuum line between the MCU, the vacuum pump and the ducting.

3.2 Services

3.2.1 Power

Check that the voltage specified on the rear of the MCU (and the vacuum pump if supplied) is correct for your supply. Except in the case of the UK and Eire, the user is responsible for providing suitable connections to mains power using the cable supplied. This is colour coded as follows:

Green/yellow Earth/Ground

Brown Live

Blue Neutral

This equipment must be earthed/grounded.

3.2.2 Fuel and Air Supplies

The HFR400 system requires:

A supply of pure (99.9%) dry, hydrogen regulated to 3.0 bar gauge.

A supply of zero grade (below 1ppm propane) air regulated to 6.0 bar gauge.

A suitable flow restrictor and/or flame trap may be fitted between the hydrogen supply and the MCU. A hydrogen generator (converting de-ionised water) is available from Cambustion.

3.2.3 Vacuum Supply

If Cambustion has not supplied a vacuum pump, then a pump, which produces a perturbation-free vacuum of at least 500mmHg (gauge) at a flow rate of at least 2000cc/min per HSM, should be used. In this case a length of black 6mm OD piping with a snap connector will have been supplied with the system. Connect the bare end of this pipe to the pump inlet.

3.3 Connections

Numbers in brackets () refer to Figure 2.4.

3.3.1 Fluids

The HFR400 system uses 3 types of snap connector for fluid connections. There are two types of large 6mm connectors, one, which only fits the hydrogen fuel line, and two others that fit the vacuum and air lines. These are connected with a firm push, and disconnected by pulling on the collar of the female. The miniature type are connected by compressing the outer sleeve of the female in order to admit the male connector and disconnected in the same manner.

Fuel Connect the fuel inlet to your hydrogen supply. Cambustion recommend the use of stainless steel tubing for this where possible. The MCU will accept either a keyed male

Swagelok fitting part No. SS-QC4-D-400K2 for 1/4" fittings or part No. SS-QC4-D-6MOK2 for 6mm fittings.

Air Connect your air supply via the DCS unit to the air inlet following the same guidelines as above. Further instructions can be found in Section A.3.2 of the DCS Manual (Appendix A).

Vac If Cambustion has supplied a vacuum pump this will connect directly to the VAC inlet. If not, you will need a vacuum of at least 500mmHg (gauge), with a capability of at least 2000cc/min STP per FID in use.

The sampling head is connected to the MCU via a conduit of length 10metres, the connections of which are colour coded as follows (extensions may be provided on request see Section 8.2)

Colour	Connection
white / red stripe	**FUEL**
white / blue stripe	**AIR**
Green	**FID bleed**
Blue	**CP bleed (for CP applications)**
Black	**VAC**

3.3.2 Electrical

The electrical connection between the HSM and the MCU is made with a LEMO type connector. This is connected by aligning the two red dots. Remove by pulling on the outer casing.

Output is provided via a BNC connector (18). The best way to monitor this is with a digital storage oscilloscope. It is recommended that even when logging data a monitor is maintained on the output to ensure that the system is operating correctly.

As a rough guide, if all the ions produced in the flame are collected, and using the accepted figure that 1 ion pair is produced for every 10^6 carbon atoms, (details of ion generation are given in Appendix 0) then the output from the FID should be given by:

FID current (mA)= 6.8×10^{-8}

- x sample flow cc/min, STP
- x concentration of HC sample(in ppm)
- x number of C atoms per HC molecule

So, for example a 0.1% propane sample, drawn from STP conditions, at a sample flow of 20cc/min should produce an FID current of 4.08nA, which will give an output of 2.04V when a gain of 500 is selected (at maximum span). Note again that this is a maximum figure based on 100% collection efficiency.

3.4 Initial Checks

The unit should operate as delivered, however the set-up procedure is outlined below.

Before power is applied to the unit for the first time, set the pressure regulators (11 and 12) fully anti-clockwise (turning them fully "off"). The regulators may, however, be left undisturbed during regular use.

Without any gas pressure or vacuum applied, switch on the unit. With `temperature' selected on the channel under test, check that the digital panel meter reads ambient temperature ±5°C. The temperature monitoring system is intended to give guidance information only, and is therefore not of high absolute precision.

Select FID pressure on the selector switch and check that the digital panel meter reads within 2mmHg of zero, with the vacuum supply disconnected.

Depress the start switch on the FID channel under test. The LED adjacent to the switch should turn RED which indicates low chamber temperature (less than 100°C) and correct glow plug function. As long as the light is RED, release of the start button will result in the fuel and air sup plies being switched off.

If there are any faults at this or any other stage consult Section 6.

3.4.1 Setting Fuel and Air Pressures

With the fuel, air and vacuum lines connected to the MCU (1,2 and 3), disconnect the HSM fuel and air snap connectors (4 and 5).

With the electrical connection (23) to the head made (required to open the solenoid valves), connect the test rotameter, first to the air outlet (5). Depress the start switch and adjust the air regulator (12) to obtain a flow of about300±60cc/min. This should correspond to a pressure gauge reading of between 3.0 & 5.0 bar. Repeat this procedure for Channel2.

The fuel regulator (11) should be set in a similar way although care should be taken to avoid igniting the fuel when measuring. Depress the start switch and adjust the regulator to obtain a fuel flow of about12±5cc/min. Again this should correspond to a pressure of between 1.5 & 3.0 bar. Repeat this procedure for Channel 2.

The sensitivity of the FID is affected by the fuel and air flows. When the instrument is successfully lit and warmed up, the fuel and air flows should be optimised by fine tuning in order to obtain the maximum response (at fixed FID ΔP) with a span gas input - see Section 4.7.2 or 5.8.1.

3.4.2 Checking Fuel and Air Pressures

Disconnect the fuel and air feeds to the MCU at the 6mm snap connectors on the front panel. Check that the pressure readings on both the air and fuel regulators remain at their pressurised level for at least 30 minutes after disconnection from the supplies. This indicates that no leaks

are present in either the fuel or air lines in the MCU. This test should be repeated weekly and more information is given in “Routine Maintenance” (Section 7)

If any leaks are detected, isolate the MCU from the fuel supply and contact Cambustion immediately.

4 Using the HFR400 Without a Constant Pressure System

4.1 Introduction

This chapter is relevant to users of the HFR400 system who have a constant pressure environment under test, typically those interested in sampling at atmospheric pressure (such as in a wind tunnel). For this application, the sampling system consists of just a BST (Basic Sample Tube), which is supplied with the system. Cambustion can supply on request any practical diameter and length BST.

The sample flow and response is dependent on the dimensions of the BST and on the pressure in the FID chamber, which is set by the operator. The program 'SATFLAP1' (see Appendix I) should be used to select tube dimensions and Cambustion are happy to advise where required. It may be useful to experiment with the software in order to get a feel for the behaviour of sampling systems in general.

When considering the response of the HFR400, be sure to distinguish between time constant and transit time: the time constant is normally the most important performance criterion, as this governs the fastest HC variations that can be followed. We define time constant here as the 10–90% response time of the FID output for a step input at the source. The transit time, (i.e. how long it takes a sample entering the sampling system to produce an electrical response), is normally not critical, as long as it remains fairly constant, though its value may need to be known. Appendix H contains details of the analytical basis for the software.

Thus in general the following need to be considered in designing the system:

1. Time constant or frequency response

2. Transit time from source to signal output

3. Sample flow rate—too little leads to insufficient signal, too much might lead to perturbation of the system under study or disturbance of the FID flame.

4.2 Lighting the FID

4.2.1 Choosing the FID chamber pressures

When choosing the FID vacuum, or deciding whether to change to a different BST, the SATFLAP1 software should be consulted.

It is best to operate with the highest Δp possible that does not cause FID flame instability. Instability may be observed by using a span gas at the sample tube inlet, and observing the stability of the output.

Before mounting the HSM in the chosen measuring position, we advise familiarising yourself with the system in a more convenient location.

Carefully fit the sample tube provided (the nut need only be finger tight to provide a gas-tight seal). Set the fuel and air regulators as described in Section 3.3. Adjust the FID VAC controller, to obtain a suitable FID ΔP (about 50mmHg for BST of ID 10 thou length 150mm). With these settings the FID should light, as observed on either digital panel meter if `temperature' is selected. The status LED indicator will change to yellow when the threshold temperature has been reached100±5°C, and to green when the start switch is released. For the flows given, the FID should reach a steady temperature of about 300±150°C, after about 5minutes.

If problems are encountered see Section 6.2 or 6.3. Note that lighting the FID may be made easier by increasing the fuel flow slightly, if necessary.

NB: When the FID is started for the first time, or if it has not been used for some time, it may take some time for the fuel gas to reach the FID i.e. lighting may take a few minutes.

It may be necessary to hold down the start switch for a few seconds after the LED turns yellow in order to allow the flame to become established on the nozzle or evaporate condensate collected in the FID chamber.

4.3 Operational Check

The output from the FID amplifier may indicate the 'spiking' due to atmospheric particulate hydrocarbons when sampling from the ambient atmosphere. Any HC sample brought into the vicinity of the sample tube should produce a response. It is very useful to have at least one calibration gas available at all times for calibration and test purposes. 1%, 0.1% and0.01% propane in air are useful mixtures, although most light hydrocarbon gases are acceptable (a butane cigarette lighter is a handy source of gaseous HC for leak testing etc.).

4.4 Shut Down

To extinguish the FID, simply switch the off/on/start switch to off. There is no need to adjust the regulators. The internal solenoid valves automatically shut off the fuel gas and air supply.

Basic safety considerations mean that on shutdown, compressed gas supplies should be isolated at source.

4.5 Leaks

Very occasionally, leaks may arise at the various fitting around the flame chamber (i.e. thermocouple gland, collector, glow plug and the lid) and also at the seal with the BST. For this reason the system should be periodically checked for leaks. The techniques for doing this are detailed in Section 7.1.3.

4.6 Mounting

Try to mount the HSM so that it is easily accessible and free from vibration. A suitable tripod is available from Cambustion. Two M6 holes and a camera tripod thread are provided in the base plate - note that the maximum penetration of mounting bolts must not exceed 5mm to

avoid damaging the internal pipework. In particular try to avoid mounting methods which cause a wrench to be used close to the BST sample tube as it is easily damaged.

When mounting and unmounting, try to protect the sample tube inlet as it can easily get be contaminated with dirt, fluff etc. if it brushes a surface. If the tube becomes dirty or blocked - consult Section 7.1.1

Note that the sampling head should be used with the flame axis close to vertical; operation at angles greater than about 10° to the vertical may result in flame distortion relative to the collector and signal attenuation or offset problems.

4.7 Calibration

4.7.1 Using standard calibration gases

Calibration gases can be used to check the characteristics of each sampling module and sample tube.

Having set the sample tube Δp, simply hold a pipe discharging a gentle flow of gas over the sample tube inlet, preferably with the jet axis at 90° to the tube axis. The pipe flow must not pressurise the sample tube inlet, i.e. the velocity of sample gas over the sample tube inlet must be small

The choice of calibration gas will depend on the application, but 1%, 0.1% and 0.01% propane in air are often useful.

4.7.2 Fuel / Air Optimisation

With the FID vacuum set as described above expose the BST to the chosen calibration gas. The HFR400 output should be in the range 0-10V. If the reading is constantly over 10V the reading is off scale. Reduce the gain control to give a voltage in the 0-10V range. If a steady reading cannot be achieved consult Section 6.

The fuel and air flows should be adjusted initially (using the pressure regulators 11 & 12 Figure 2.4) to the highest output response. This may require several iterations i.e. first adjust the fuel, then the air, then fuel again and so on until the optimum is achieved. To aid flame stability however, it is recommended that the hydrogen flow should be increased slightly to the point resulting in a 10% decrease in signal output from the optimum level. Always set the hydrogen regulator on the increase (clockwise) direction.

4.7.3 Span and Offset Controls

The span and offset controls may be used to eliminate zero offsets and select a convenient calibration figure (e.g. 1V=1000 ppm). Note that the offset and gain may change slightly from range to range of amplification. Try if possible to ascertain the maximum concentration to be encountered in the experiment, and then set the appropriate scale, and perform the offset and gain correction on that scale. Note also that the HFR400 like all FIDs become non-linear at very high HC mass flows.

The oxygen concentration present in the sample will have a second order effect on the calibration of the FID. This is called oxygen synergism. Ideally, the calibration gas should be chosen to have a balance having a similar oxygen concentration as the sample.

4.7.4 Gas mixing units

Commercial units are available to mix any desired proportions of zero air and a hydrocarbon gas for calibration purposes. Cambustion can advise of suppliers of such equipment.

4.8 Checking the Frequency Response

Most users will want to take advantage of the high frequency response of the HFR400 and, therefore, it is useful to be able to measure this for the particular set up in use. The frequency response is a function of sampling system tube dimensions and pressures, and the software packages should be used when designing a sampling system, and thus obtain an estimate from theoretical considerations (See Appendix I).

When a sampling system has been set up, it is advisable to check its frequency response.

Place the BST in the end of a tube supplying span gas. Increase the flow of span gas until the output reading no longer rises, make sure that the output reading is not saturated (above 10volts). If it is saturated, adjust the gain so that the output reading is below 10V. Now hold the BST about 5mm (1/4”) from the tip with one hand and flick the tube supplying the Span gas away with the other hand. This provides a step input, from 100% to 0%, to the HSM. Use a storage oscilloscope or a data logging device to record the response to the step input. The response time is the time taken for the signal to change from 90% to 10% of the span reading. Some typical results are shown in Figure 4.1. However, the exact values of the transit and response time will be governed by the dimensions of the BST.

The response time will vary from one flick to another as a result of the rapidity with which you removed the source of Span gas was removed . The fastest response time measured will be the one which most accurately reflects the response time of the sampling system.

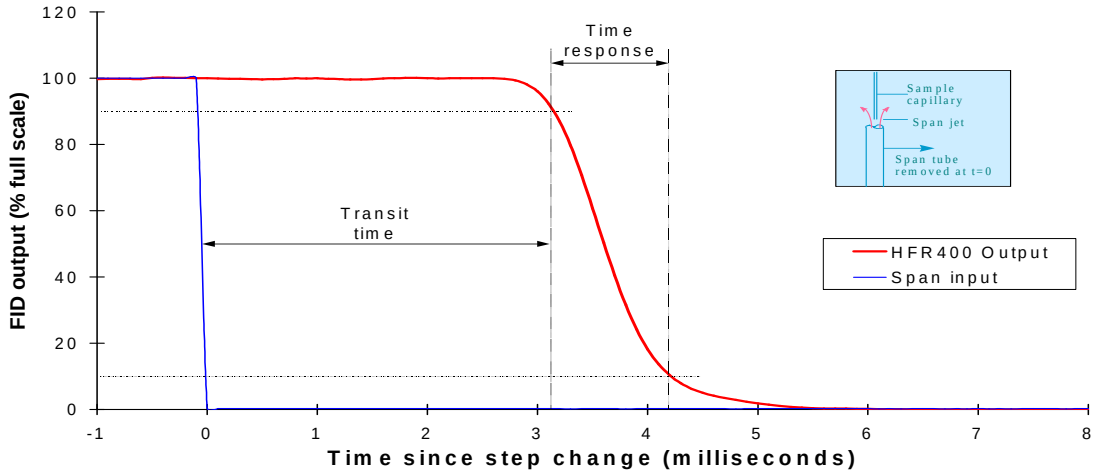

Figure 4.1 – Typical Flick-test response

5 Using the HFR400 with a Constant Pressure System

5.1 Introduction

Users of the HFR400 who are taking measurements where the sample pressure fluctuates with respect to ambient by more than a few inches of water will almost certainly wish to use a HSM with a constant pressure (CP) chamber already fitted, along with suitable sample lines.

5.1.1 Sample Flow Considerations

When considering the response of the HFR400, be sure to distinguish between *time constant* and *transit time*: the time constant is normally the most important performance criterion, as this governs the fastest HC variations that can be followed. We define time constant here as the 10–90% response time of the FID output for a step input at the source. The *transit time*, (i.e. how long it takes a sample entering the sampling system to produce an electrical response), is normally not critical, as long as it remains fairly constant, though its value may need to be known. Appendix H contains details of the analytical basis for the software.

In general the following need to be considered in designing the system:

1. Time constant or frequency response

2. Transit time from source to signal output

3. Sample flow rate: too little leads to insufficient signal, too much might lead to perturbation of the system under study or disturbance of the FID flame.

4. Condensation of the HC sample: potentially a problem when sampling from a liquid fuelled engine.

A complete analysis of the sample tube flow is not trivial. However, it is very useful, and this is why the software package SATFLAP3 has been developed - see Appendix H

5.2 Operating Principle of CP Chamber

The function of the CP chamber is simple, to remove the effect of upstream pressure fluctuations on the flow rate of sample into the flame chamber, so that an unbiased concentration measurement is obtained. Figure 5.1 is a diagram showing how this is achieved.

The *sample line* carries the sample from the source to the CP chamber. It is physically a separate item from the CP chamber but easily joined to it.

The *tee top* and *FID tube* are joined inside the CP chamber. The *tee top* always has a larger inside diameter than the ID of the sample line, so that the velocities within the tee top are reduced from the very high values which can exist at exit from the sample line.

The FID tube forms a static tapping on the changing sample flow through the tee-top. Therefore there is no dynamic pressure ($\rho v^2/2$) effect on the FID tube flow.

It is important that variations of flow into the CP chamber do not cause the pressure there to change significantly. The bleed flow regulators remove pressure changes on a relatively long time scale, but very short time scale fluctuations are minimised by making the effective CP chamber volume large compared to sample flow fluctuations. The effect of short time-scale fluctuations on the sample flows is minimised by operating with a high as possible FID Δp pressure (limited by flame stability considerations). It is necessary to operate with a CP chamber pressure low enough to supply the requirements of the FID tube under all conditions of sample source pressure.

Typically, for engine exhaust applications with a 330mm long, 26 thou ID Heated Transfer Sample Line (TSL-H), a CP gauge pressure of 350 mmHg, and an FID Δp of 100mmHg are recommended with a standard 0.008" FID tube (denoted with yellow marker, 0.010" i/d with blue marker).

If pressure fluctuations are still a problem, due for example to very high pressure fluctuations in the exhaust, then fitting an extension volume of the order of 5cc or more onto the base of the CP chamber will help considerably.

5.3 Lighting the FID

Before mounting the HSM on the engine it is worth gaining some experience with the instrument in open air.

Carefully attach the TSL to the HSM. It need only be screwed finger tight to give a good seal.

Having set the fuel and air regulators as described in Chapter 3. Adjusting the FID and CP VAC controllers, to obtain an FID Δp of about 80mmHg CP Vac of 350mmHg. With these settings the FID should light, as observed on either the digital panel meter if 'temperature' is selected, or on the status LED indicator which will change to yellow when the threshold temperature has been reached100±5°C), and to green when the start switch is released. For the flows given, the FID should reach a steady temperature of about 300±150°C, after about 5minutes.

If problems are encountered see Section 7.1.2 and 7.1.3. Note that lighting the FID may be facilitated by increasing the fuel flow slightly.

NB: When the FID is started for the first time, or if it has not been used for some time, it may take some time for the fuel gas to reach the FID.

It may be necessary to hold down the start switch for a few seconds after the LED turns yellow in order to allow the flame to become established on the nozzle or evaporate condensate collected in the FID chamber.

5.4 Operational Check

Observation of the output from the FID amplifier may indicate the characteristic ‘spiking’ due to atmospheric hydrocarbons at the higher gain settings. Any HC sample brought into the vicinity of the sample tube should produce a response. It is very useful to have at least one test gas available at all times for calibration and test purposes. 1%, 0.1% and0.01% propane in air are useful mixtures, although most light hydrocarbon gases are acceptable (a butane cigarette lighter is a handy source of gaseous HC for leak testing etc.).

5.5 Shut Down

To extinguish the FID, simply switch the *off/on/start* switch to *off*. There is no need to adjust the regulators. The internal solenoid valves automatically shut off the fuel gas and air supply.

For safety reasons it is important that on shutdown, the supply of compressed gases is turned off at source.

5.6 Leak testing

This is an important aspect of the system as it can indicate problems with the seals etc. around the CP system and if carried out during sampling from fluctuating pressures provides a good check that the CP and FID pressures are set correctly. If not, the leak check procedure will show an apparent leak not present whilst leak testing in atmospheric conditions. This part of the operation is so important that it has been given it own section. See Section 7.1.3.

5.7 Installation Considerations

Figure 7.2 is an exploded assembly of a HSM fitted with a CP chamber. Most users will have been supplied with a complete system, including the sample line.

The user must make the following decisions:

5.7.1 How best to fit the sample line to the engine

The standard sample line has an OD of 1/8" and the DCS400 Calibration Adapter (CAL-APT) has an O/D or 3/16”, so a suitable compression fitting should be mounted in the exhaust. Cambustion supply two ¼”NPT fittings for mounting the CAL-APT in the exhaust. The overall length of the sample line will determine possible sampling locations. Cambustion can supply custom-made sample lines if required.

5.7.2 How to mount the HSM

There are two tapped 6mm ISO metric holes and one camera thread hole in the baseplate of the HSM which may be used for mounting (care must be taken not to use bolts which are too long and may damage the fuel supply pipe which runs on the other side of the baseplate). It is most important to avoid excessive stress of the sample line, while keeping the HSM approximately upright. It is very useful to be able to remove the TSL from the HSM from time to time for cleaning etc. The HSM itself should be isolated from excessive vibration which may cause interference on the signal.

5.7.3 What pressure to set in the FID and CP chamber

Note that once suitable operating pressures have been set, they will not need to be altered for a particular set-up. As mentioned above, for a typical exhaust sampling arrangement (0.008" FID tube, 26 thou ID, 330mm long TSL-H), a CP chamber pressure set on the display of 350mmHg (i.e. 350mmHg below atmosphere) is sufficient to ensure a sufficient sample flow from the exhaust to the HSM even when the exhaust pressure instantaneously becomes sub-atmospheric. The FID pressure should be set to about 80 mmHg (for 0.008" FID tube) below the CP pressure (i.e. a Δp of 80 mmHg).

Once set, the vacuum controllers should only require minimal adjustment during operation.

SATFLAP3 may be useful to establish the approximate time constants and transit times for the sampling system (see appendix I) which correspond to the pressures chosen.

5.8 Calibration

The easiest way to calibrate is simply to flood the sample line inlet with span and zero gas alternately.

5.8.1 Fuel / Air Optimisation

With the sample tube exposed to the chosen calibration gas adjust the gain control to give a steady DC voltage in the range 0-10V (if it does not refer to Section 6.8). The fuel and air flows should be adjusted using the pressure regulators (11 &12 Figure 2.4) to obtain the best output response (highest voltage). This may require several iterations i.e. first adjust the fuel, then the air, then fuel again and so on until the optimum is achieved.

5.8.2 Span and Offset Controls

The span and offset controls may be used to eliminate zero offsets and select a convenient calibration figure (e.g. 1V=1000 ppm). Note that the offset and gain may change slightly from range to range of amplification. Try if possible to ascertain the maximum concentration to be encountered in the experiment, set the appropriate scale, and perform the offset and gain correction on that scale. Note also that FIDs become non-linear at very high HC mass flows.

This calibration technique, however, does not allow the system to be calibrated at the same conditions as the test itself. In particular, it is important to establish any effect of pressure fluctuations in the exhaust on the FID response. Dynamic calibration is required for this.

5.8.3 Dynamic calibration

A DCS400 calibration system is available which provides rigorous dynamic calibration. It is described in a separate manual enclosed in the same case as this user-guide. Contact Cambustion for details.

5.9 Checking the Frequency Response

The frequency response of the sampling system may be estimated in the following way. Arrange a jet of span gas along the axis of the TSL-H with the span gas exit as close as possible to the TSL itself. Rapidly deflect the TSL-H out of the jet into the adjacent air. The 90–10% response time may be easily determined from the resulting signal. The result should appear similar to that shown in Figure 4.1 – however the transit time will be of the order of 6 milliseconds, and the response time approximately 4 milliseconds for the standard system. The values for transit and response time are governed by the dimensions of the sampling system and the settings of CP and Δp.

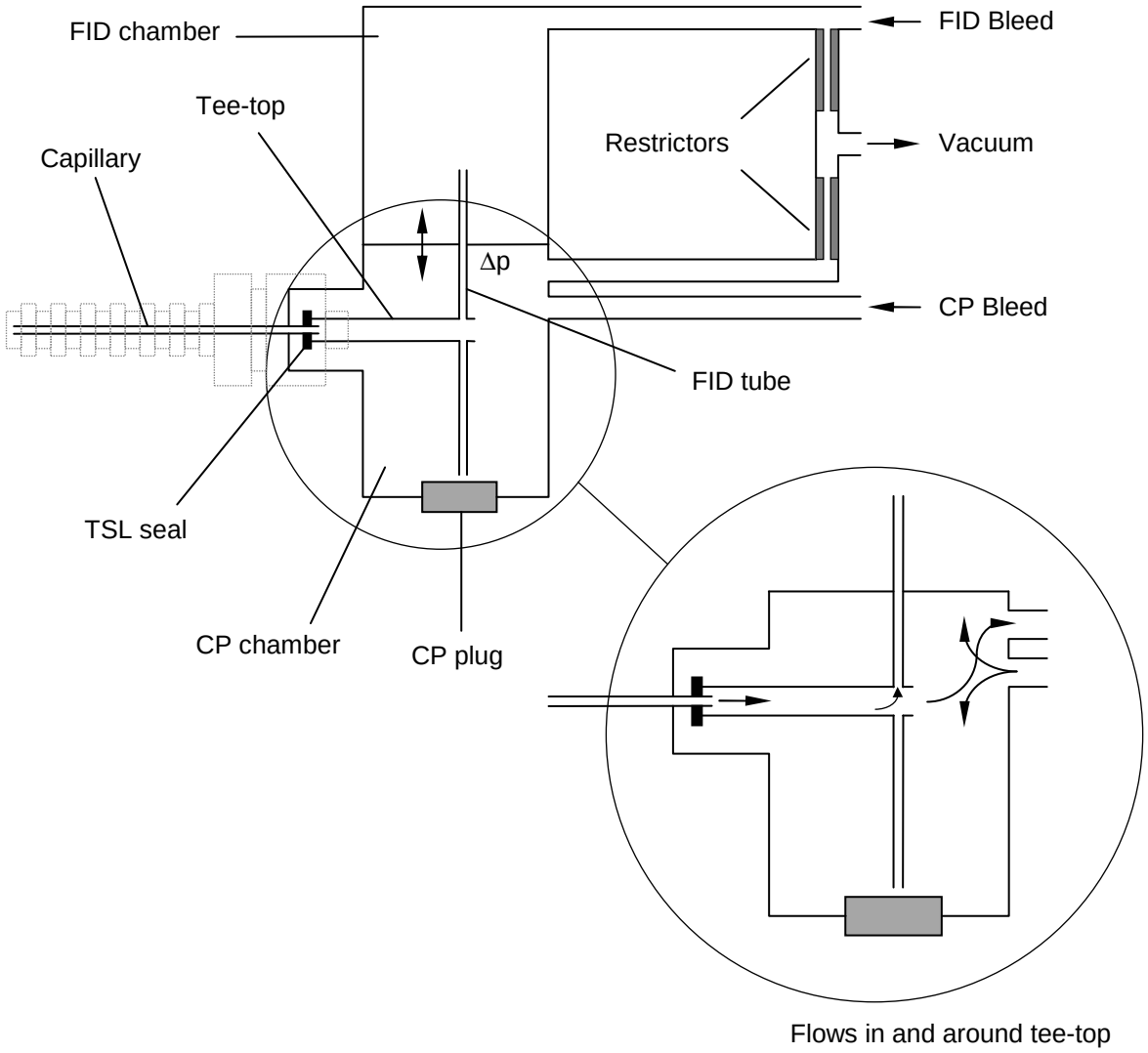

Figure 5.1 – CP Sampling system

6 Troubleshooting

6.1 Introduction

We have tried to cater for most problems that occur in this section. However, it is impossible to cover all eventualities. If you do encounter problems please do not hesitate to contact Cambustion. We find that most things can quickly be diagnosed by a phone call, FAX or email message.

6.2 Contact

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Since the HFR400 is a 2-channel instrument, it is normally quite easy to establish whether the fault is on channel 1 or 2 of the MCU or on one of the HSMs.

The following sub-sections describe some common problems and the steps required to cure them.

6.3 Required vacuums cannot be achieved

Possible cause : Incorrect connection/leaks/blocked vacuum restrictor

Check that the connections have been correctly made at MCU (See Section 2.3)

Check that TSL-H is fitted to HSM.

Check black vacuum pipe connections at HSM.

Leak test (7.1.3).

Check if vacuum is supplying vacuum.

N.B. The maximum vacuums possible will be reduced when running both channels.

6.4 LED does not illuminate when start switch depressed

Possible cause : Electrical connection not made – Broken glow plug

Check the electrical connections. Try HSM on other channel of MCU.

If this fails contact Cambustion who will supply a new glow plug. Fitting is described in Section 7.2.5.

6.5 LED illuminates red but temperature does not rise

Possible cause: Incorrect fuel/air flows – Leak into FID Flame Chamber–Faulty glow plug

The start switch may require several depressions to start the flame. If this fails check the fuel and air flows as described in Section 3.3.1

If the HSM still fails to light try varying the fuel/air flows whilst holding down the start switch. Reducing the CP vacuum may help. Once the flame is lit the CP pressure can be re-set to the desired value.

Serious leaks at the collector, thermocouple gland, glow plug, FID lid or collector hatch will also cause lighting problems. Check these fittings for tightness (see Section 7.1.3).

If problems persist this suggests a problem with the glow plug.

If extension cables are fitted it may be necessary to increase the current flow to the glow plug. This is a simple modification and Cambustion can supply the necessary parts and instructions. Otherwise it may be necessary to replace the glow plug. Cambustion will be happy to supply the necessary parts and fitting instructions.

6.6 Output has large persistent offset

Possible cause : Condensation –Thermionic emission –offset potentiometer badly adjusted

The offset potentiometer may be checked with the head extinguished (i.e. LED out) but the *off/on/start* switch in the *on* position.

Condensation can become deposited on the collector when the instrument is switched off. This can produce a very large initial offset signal when the instrument is next used. Usually as the HSM warms up with normal operation the condensation evaporates and the offset disappears.

If the offset takes a long time (over 30 mins) to disappear the collector insulator may be dirty. The position of the collector should also be checked as detailed in Section 7.2.3. If, however, problems persist, remove and clean as detailed in Section 7.2.2.

6.7 Noisy signal

Possible cause: Excessive/insufficient sample or fuel/air flows – leaks

The most likely cause of a noisy signal is a leak in the sampling system. Leak test as described in Section 7.1.3.

Drawing an excessive amount of sample into the flame can cause it to become unstable leading to a noisy signal. Consult the SATFLAP software and note the sample momentum flux. If the value is flashing then the flame may be unstable. Adjust the pressure selected for the sampling system accordingly.

6.8 Dynamic calibration does not produce a flat signal

Possible cause : Insufficient Span gas pressure – Low pressures at sample point.

Increasing the span gas pressure. See Troubleshooting section of DCS400 User Manual (Section A.7).

If the calibration signal shows dropouts which are periodic with engine cycles this suggests that at some time in the cycle, the pressure at the sampling point drops to near or below that in the CP chamber. Therefore, at this point there will be insufficient or no flow along the TSL to satisfy the FID tube (in fact the flow may be reversed). This can be a problem especially when using long TSL-Hs. Check this by directing the jet from an unlit cigarette lighter at the TEST point on the MCU whilst calibrating. The dropouts should change to peaks if this is the case.

Slowly increase the CP vacuum and the dropouts should disappear. It will also help to reduce the value of ΔP especially if very high CP vacuum (over 400mmHg) is required.

6.9 Different calibration before and after experiment

Possible cause : Blocked TSL-H or FID tube

Clean TSL-H and FID tube (See Sections 7.1.1 and 7.1.2).

6.10 Very low signal / poor frequency response

Possible cause : Blocked TSL-H or FID tube

Clean TSL-H and FID tube See Section 7.1.1 and 7.1.2.

6.11 Excessive span drift

Possible cause: Fuel/air flows not optimised–Collector overheating

Changes in the temperature of the sampling system will cause variations in calibration. This is why the dynamic calibration is so important as not only the pressures but also the temperatures are similar to those experienced during the experiment.

However, if excessive span drift is experienced, check that the fuel and air flows are optimised for the span gas chosen, see Sections 4.7.2 or 5.7.1.

If this does not cure the problem the collector may be incorrectly positioned leading to overheating. Check the collector position as described in Section 7.2.3.

7 Maintenance

7.1 Routine maintenance

7.1.1 Cleaning TSL-H or BST

Frequency : Daily or if blockage is suspected

Unscrew the TSL-H/BST from the HSM.

TSL-H only –The retaining collar for the modified TNC connection should be loosened and these items removed. This will allow inspection of the TSL seal which should be replaced if damaged or worn.

Push the cleaning wire supplied in the tool kit through the TSL-H/BST - a small pair of long nosed pliers is ideal for this. If a blockage is particularly stubborn, application of a solvent (acetone) and gentle heating with a hot air gun will help.

TSL-H only -Reassemble the TNC connector and retaining collar.

7.1.2 Cleaning the FID tube (CP system)

Frequency : Every 2/3 days or if blockage suspected.

Important - Always move the off/on/start switch to off and disconnect the electrical cable before attempting to clean the FID tube.

Remove the brass CP bleed plug from the bottom of the CP chamber. Pass the appropriate cleaning wire through the hole in through the FID guide tube. The tee-pieces and cleaning wires are colour coded: yellow for 0.008” i/d and blue for 0.010”.

7.1.3 Leak testing

Frequency : Daily and immediately before important measurements.

Leak testing is an extremely important aspect of the system. Failure to leak test could result in invalid measurements.

An un-lit cigarette lighter is the ideal tool for leak testing. It produces a very concentrated (10^6 ppm !) jet of butane. The jet can be directed at the various seals and potential leaks sites in the system. Any leaks will clearly show up as a very large spiky signal on the output when the FID is alight.

The list in Sections 7.1.3.1 to 7.1.3.5 details the possible leaks sites and suggested remedies if leaks are found (refer to Figure 7.1).

The list is primarily for those users with CP systems. Atmospheric users need only leak test the connection between BST and HSM and then the areas in Sections 7.1.3.4 and 7.1.3.5.

7.1.3.1 Test point (MCU)

This is by far the most useful test and can be carried out quickly and easily at the MCU. It should be repeated as often as is practical and especially before important measurements when sampling from fluctuating pressure environments.

The test point is the admission point for the bleed air flows of the system which control the CP and FID pressures. Therefore, directing a jet of butane gas at this point will quickly replace the gas in the CP chamber with very concentrated HC. Any problems with the CP system will quickly show up. To convince yourself of this, try blocking the sample line and then directing the butane jet at the test point—a large spikey signal will be seen. Alternatively, try reducing the CP gradually whilst using butane at the test point. As the CP pressure is reduced there will come a point at which the flow along the sample line is insufficient to satisfy the FID tube flow. The FID tube will then take flow from the CP chamber instead causing (in this case) a large spiky signal.

A signal produced by applying butane at the test point has several potential causes

1. Poor seal between TSL-H and HSM. Try tightening the TNC connector slightly. If this fails, remove the TSL-H from the HSM. Unscrew the retainer from the TSL –H and remove the TNC connector. Inspect the seal and if necessary replace (refer to Figure 7.2).

2. Blocked TSL-H. If the TSL-H becomes blocked then the FID sample is taken from the CP chamber. Remove the TSL-H and clean as detailed above.

3. Δp too high/ CP Vac too low. This is especially important when leak testing during sampling/calibrating from a varying pressure (e.g. engine exhaust). If the pressure at the sample source falls too near or below that in the CP chamber then there will no longer be sufficient flow along the TSL-H to satisfy the sample flow into the flame. Therefore, the flame begins to sample from the CP chamber as well as the sample point. The problem is exacerbated by the fact that as the sample line becomes hot this too restricts the flow along it. If there is insufficient flow along the TSL-H this appears as a leak. A solution is to increase the CP vacuum and/or reduce the Δp. If this remains ineffective contact Cambustion as it may be necessary to use a larger diameter sample tube.

4. A likely cause is that one of the seals inside the CP system have become worn. Strip down the system as detailed below. Inspect the O ring seals on the flame nozzle and the grub screws and their seals which hold the tee-piece in position and replace as necessary.

7.1.3.2 TNC connector

Almost certainly a poor seal between TSL-H and HSM. See point 1 above.

7.1.3.3 CP chamber gasket seals

Slight leaks in these seals are less significant since they merely add to the bleed flow already issuing from the CP bleed flow. Larger leaks may lead to problems with the vacuum regulation.

If leaks are found at the CP chamber gasket seals, strip down the CP system (see below) and replace.

7.1.3.4 Inspection hatch

Probably a failed O-ring under the inspection hatch. Remove inspection hatch using C spanner supplied and replace, being careful not to cross the threads.

7.1.3.5 Inside the perforated HSM cover

If directing the lighter jet into the perforated cover produces a signal, this suggests a leak at either the collector or the glow plug.

Remove the cover and by further testing identify the leaky component (refer to Figure 2.3).

The most likely source is the glow plug. Disconnect the LEMO electrical connection to the HSM. Tightening the glow plug with the box spanner provided in the tool kit may cure the problem. If not, loosen the plug. To do this it is usually easier to cut the electrical connection - the orange wire. Apply a little silicon grease to the threads of the glow plug and retighten, onto the copper washer. Re-solder the electrical connection and recover with a little heat shrink. Replace the perforated cover,

If the collector is at fault remove the collector as detailed in Section 7.2.2. Inspect and if necessary replace the O ring seals.

7.2 Servicing Procedures

7.2.1 Stripping down the CP system

The seals contained within the HSM are Viton. At the high temperatures encountered within the HSM these will deteriorate over time. This can easily be detected using the leak testing procedure detailed above. This section describes how the CP system may be dismantled so that they may be inspected and changed.

When dismantling the CP system take care not to lose any of the screws. Most of them are non-standard and would have to be supplied by Cambustion.

7.2.1.1 To strip down the CP system

Please refer to Figure 7.2.

1. Disconnect the TSL-H from HSM.

2. Disconnect the HSM from MCU.

3. Remove the lower 2 of the 4 screws which fix the male TNC connector to the HSM and CP chamber.

4. Remove the 3 screws which retain the CP chamber.

5. Remove the CP chamber and its gasket exposing the tee-piece.

6. Unscrew the grub screw which locates the tee-piece into the TNC connector (with a pair of longnose pliers).

7. Remove the remaining 2 screws which attach the male TNC to the HSM.

8. The TNC should now pull away from the tee-piece. Be careful to support and not to damage the tee-piece during this operation.

9. Remove the grub screw from the tee-piece and the corresponding seal (which may be retained in the TNC connector).

10. Unscrew the remaining grub screw which locates the tee-piece into the flame nozzle. Again the grub screw seal may remain in the nozzle. This seal is the most likely cause of internal leaks, as it deforms with time more rapidly than the other seals in the HSM.

11. Remove the tee-piece.

12. As a matter of routine it is probably worth cleaning the FID tube with the 0.007" cleaning wire supplied whilst the system is dismantled.

13. Remove the flame nozzle using the C spanner provided. It should have 2 associated O rings.

7.2.1.2 Re-assembly

Re-assembly is exactly the reverse of assembly.

When re-assembling the CP system remember the following

1. Check that the flame nozzle has both O rings. Be careful not to cross the fine threads when refitting the nozzle.

2. Fit both grub screws and new seals on the tee-piece before fitting into the flame nozzle.

3. Initially fit the upper 2 screws on the TNC connector very loosely (this helps when locating the grub screw at the rear of the TNC. When the remaining 2 screws have been fitted (after the CP chamber) tighten all 4 in sequence.

7.2.2 Removing the collector

The procedure for removing the collector is as follows (refer to Figure 2.3)

Remove the perforated HSM cover.

Disconnect the electrical cable at the bulkhead of the HSM.

Loosen the nut which retains the socket (which should be finger tight).

Withdraw the socket through the bulkhead (this will separate the grey plastic collector assembly - a small flat-bladed screwdriver may help to separate these if they are tight). Be careful not to stress the 4 wires connected to it. The collector should now pull out from its housing and will pass through the hole in the HSM bulkhead.

Clean the collector with a solvent (such as iso-propyl-alcohol or trichloroethane). N.B. Water based solvents must not be used.

The most important area is the face of the insulator which is exposed to the flame chamber.

Replace the collector by reversing the above sequence. Take great care when replacing the electrical socket into the bulkhead not to damage the collector connections. If problems persist contact Cambustion.

7.2.3 Collector location adjustment

If an offset builds up over the first few minutes of use and then does not go away this suggests that the collector itself may be incorrectly positioned.

If the collector sticks out too far over the flame it can become overheated causing large offsets due to thermionic emissions. To investigate: Turn the on/off/start switch to off and disconnect the electrical cable.

This is very important - the collector runs at very high voltages. Serious damage and/or injury could result from tampering with the collector whilst the device is still `on'.

Remove the collector hatch cover with the C spanner provided in the tool kit (see Figure 7.1) The correct depth of the front face of the collector is 12mm from the front outside face of the HSM. Vernier callipers, used as a depth gauge, are ideal for this measurement.

Inward adjustment to the collector or location may be made simply by pushing gently with the vernier callipers. Outward adjustment may be achieved with a pair of long nosed pliers but may require removal of the whole collector assembly the procedure for which is outlined in Section 7.2.2.

7.2.4 Leak checking the Main Control Unit

The compressed gas supplies to the MCU should be shut off at source at shutdown of the equipment. However, with both channels switched off, there will be compressed gas remaining inside the MCU. The pressure of this gas may be monitored on the front panel pressure gauges. Falling of these pressures when the gas sources are shut off indicates a leak inside the MCU. The severity of the leak is indicated by the rate of fall of these pressures - slight leaks giving pressure drifts on a time-scale of days may be disregarded. More severe leaks require the unit to be closed down, all gases to be turned off and Cambustion to be contacted immediately.

7.2.5 Removal/Refitting of Glow Plug

Failure or leakage of the glow plug may lead to its replacement. The procedure for this is outlined below. Refer to Figure 2.3. A new glow plug and special box spanner is now available from Cambustion.

1. Disconnect HSM from MCU and remove perforated cover.

2. Disconnect electrical cable from HSM.

3. Cut electrical connection to the glow plug, remove used heatshrink sleeving and prepare end of cable for resoldering.

If glow plug leaks, the box spanner provided in the toolkit to the collector axis to loosen the glow plug by 3 or 4 turns. Apply a small amount of silicon grease (or similar) to the threads of the glow plug and retighten onto the copper washer.

If the glow plug has failed, remove and discard the glow plug and washer and replace with a new glow plug/washer. Locate the glow plug in the threads of the flame chamber and then treat them with a small amount of silicon grease. Tighten plug onto copper washer and replace electrical connection using 3mm ID adhesive lined heatshrink or similar.

If the glow plug is difficult to loosen, gentle heating with a hot air gun (being careful not to damage the other head wiring) may help release it.

7.2.6 Cleaning flame chamber

After a great deal of usage (typically once per year or so), it may be beneficial to clean the flame chamber and nozzle of the FID.

The procedure for doing this is outlined below. Refer to Figure 2.3.

Disconnect HSM from MCU and remove perforated cover. Remove FID lid and gasket (retained by 4 off M2 Allen key head bolts) and collector hatch together with O ring (using C spanner supplied in toolkit).

Remove collector (see Section 7.2.2).

Remove CP chamber assembly (see Section 7.2.1).

Remove FID nozzle, together with its 2 O rings (using C spanner in toolkit).

The FID flame chamber, stripped down as far as it can be, may now be placed in a close fitting glass beaker filled to a level which just submerges the flame chamber with a non-aqueous benign solvent (Trichloroethane, Methylated or similar - solvent must not attack the conductor insulation of the glow plug connection or leave deposits in the flame chamber). An ultrasound bath may be used to cleanse the HSM.

The other separate parts of the assembly may be cleaned in a similar manner - do not ultra-sound seals and O rings which may absorb the solvent and lead to persistent offsets.

Replace seals and O rings as required.

Assembly is the reverse procedure. Note that large offsets will persist until all traces of solvent have been purged from the flame chamber.

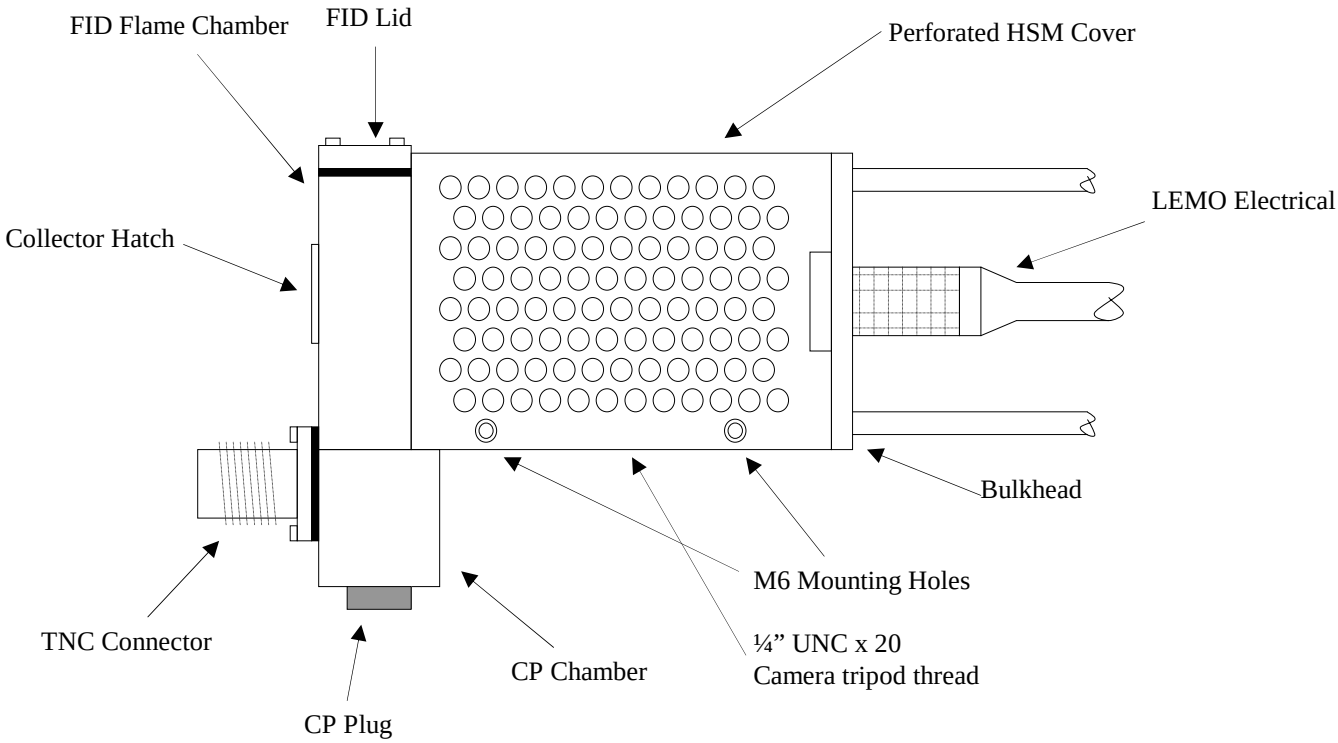


Figure 7.1 – External View of HSM (sampling head)

7.2.7 Disconnecting HSM from Umbilical

Follow these instructions when disconnecting the sample head from the Umbilical.

1. Ensure that the system has been switched off, and allowed to cool.
2. Remove the TSL-H (Heated Sample Line) from the head.
3. Remove the electrical LEMO connector from the back of the HSM.
4. Disconnect the fuel and air supplies at the 1/8" Swagelock unions.
5. Disconnect the FID Vac, FID Bleed & CP Bleed at the 6mm Push-fit unions.
6. Disconnect the CP Vac at the 6mm Push-fit Y-connector.

Once disconnected, the sample head and TSL-H (heated sample line) can be returned to Cambustion for servicing.

Re-fitting is the reverse of the above instructions.

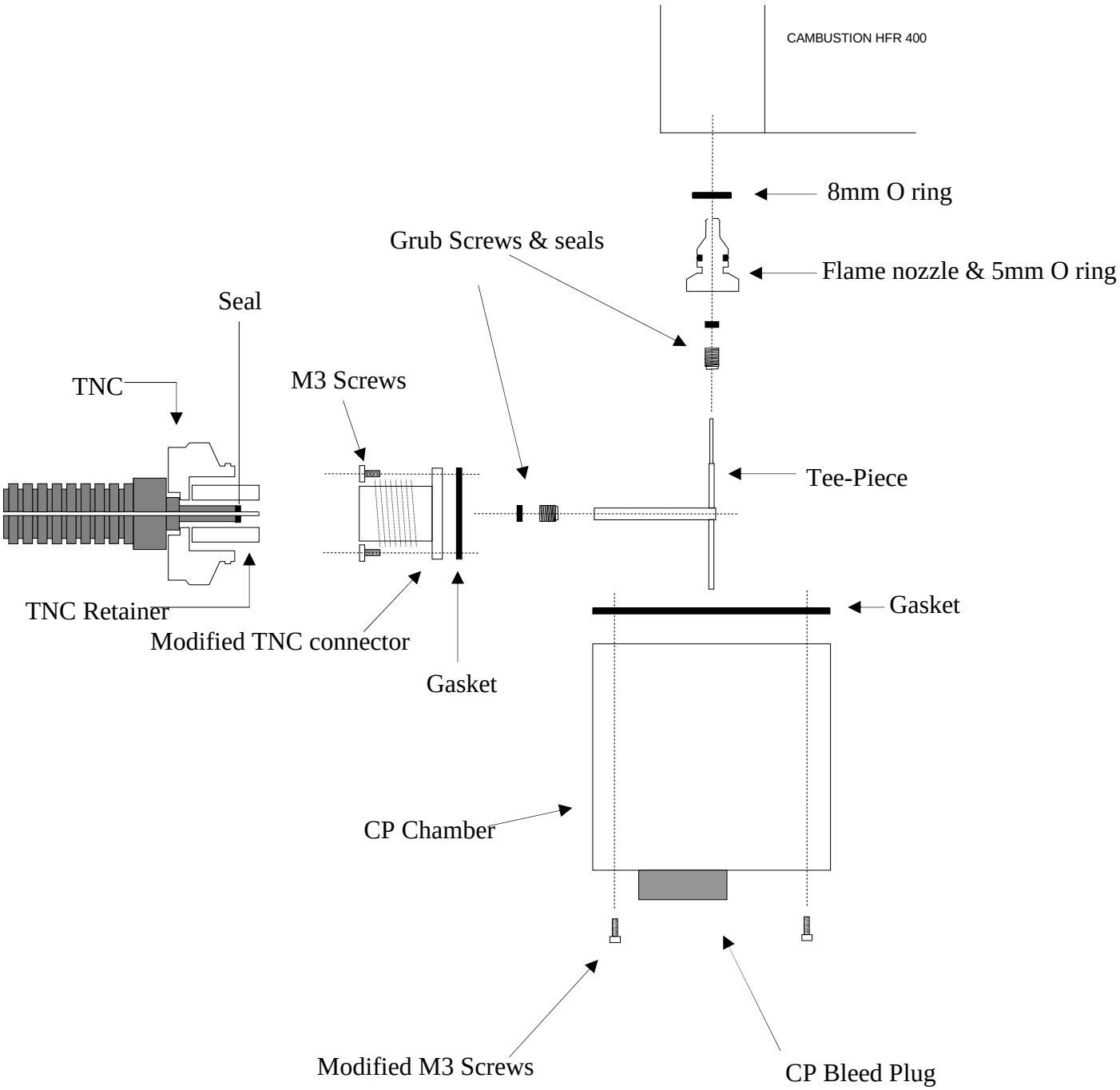


Figure 7.2 – CP System Assembly

8 Accessories

8.1 Basic Sample Tube (BST)

This item is supplied for sampling from constant pressure environments. Any length and tube diameter can be supplied—the choice will depend entirely on the experimental arrangement.

The frequency response of the system is dependent on the length of the tube, and the pressure difference across it. The sensitivity is dependent on the mass flow rate, which largely depends upon the pressure difference across the tube, its diameter and its length. The range of flow rates normally used is in the range 25—100cc/min. Typical situations are tabulated below for a flow of 50cc/min, from which others may be approximately interpolated for initial design purposes.

L(mm)	Δp (mm Hg)	tube size (in)	Time Constant (ms)
50	50	0.010	0.81
100	100	0.010	1.13
300	250	0.010	2.05
1000	400	0.012	5.29
2000	400	0.016	10.6

It is possible to obtain very good response times with longer sample tubes by using a constant pressure system. However, a large sample flow is necessary, typically of the order 5 l/min which may be problematic for some users.

8.2 Heated Sampling Line (TSL-H)

The heated sample lines are supplied with the HFR400 as standard. Heating the sample lines prevents any liquid droplets from condensing in the lines and smearing along the tube walls causing a loss of frequency response, or in extreme cases extinguishing the FID flame.

These lines are made with a modified TNC connector at one end, and rigid length of 1/8" stainless steel at the other.

The connector to the CP chamber allows easy, repeatable, leak-tight connection to the CP chamber and locates the sample tube precisely relative to the tee-piece.

The TSL-H inside diameter is chosen on the basis of the required length and sample pressure fluctuation. The sampling tube ID is normally 26 thou (0.66mm), but for in-cylinder sampling an insert is used to reduce the ID, to prevent excessive sample flows at high cylinder pressure. See Section C.5.2 for details.

However, note that the time constant and transit time both deteriorate with increasing length. Cambustion will advise, on the basis of a computational model, the optimum configuration for your needs.

8.3 DCS-400 Dynamic Calibration System

The DCS is described in detail in Appendix A.

8.4 Line Heater Controller (LHC)

The LHC is described in detail in Appendix B.

8.5 Sampling Spark Plug (SSP)

In-cylinder sampling, the SSP and the data obtainable using it are described in detail in Appendix C.

Further details can be supplied on request.

8.6 Hydrogen Generator

This is a stand-alone unit that produces pure, dry Hydrogen at up to 4 bar by electrolysis of water. The flow rate is sufficient to operate 2 heads simultaneously. In this way, the requirement for highly compressed Hydrogen is removed and the portability of the system is greatly improved.

Further details available on request.

Appendices

A Dynamic Calibration System (DCS) Manual

A.1 Introduction

This manual provides information on the operation of the Cambustion DCS400 Dynamic Calibration System. The DCS400 allows the user to remotely control

SPAN A

SPAN B

ZERO

SAMPLE

and PURGE

functions on the HFR400 and *f* NOx400 without disturbing the sample line.

The DCS400 is intended only for use with the HFR400 and *f* NOx400 systems and must only be used for gaseous samples. For safety reasons, it is important that the sample tube will never ingest liquids, which may collect at the sampling location. This is particularly important if liquid gasoline is present as this may result in damage to the DCS400 and presents a safety hazard.

A.2 Overview

The DCS400 provides simple but rigorous calibration during engine running without the need to disturb the calibration sample line. This is achieved (see Figure A.2) by subjecting the span gas at the sample tube tip to the same pressure and temperature perturbations as are present at the sampling point (e.g. in the exhaust port). A flat response to the span gas while the engine is running confirms pressure independence and validates signals being generated. The signal level gives the calibration and also indicates whether the sampling system is blocked. The DCS400 system is superior to other calibration systems which simply introduce span gas directly into the reaction chamber. Such systems only provide a calibration value and neglect the important elements of sample pressure independence and sample system blockage.

Span, zero or purge air is directed to the tip of a heated sample line (TSL-H) using a (3/16" outside diameter) calibration adapter (CAL-APT). The construction of the calibration adapter is shown in Figure A.1.

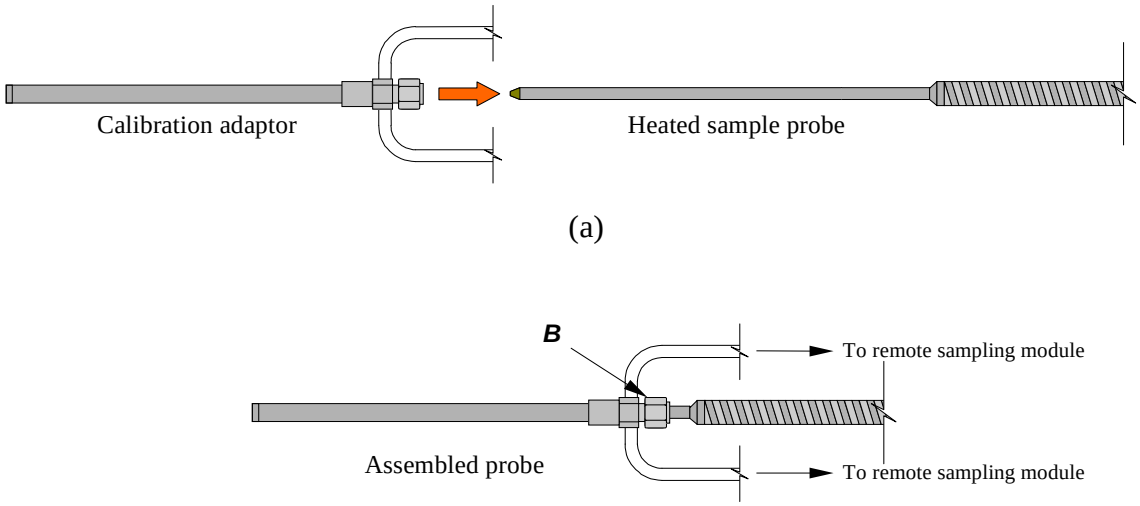


Figure A.1- Fitting CAL-APT to TSL-H

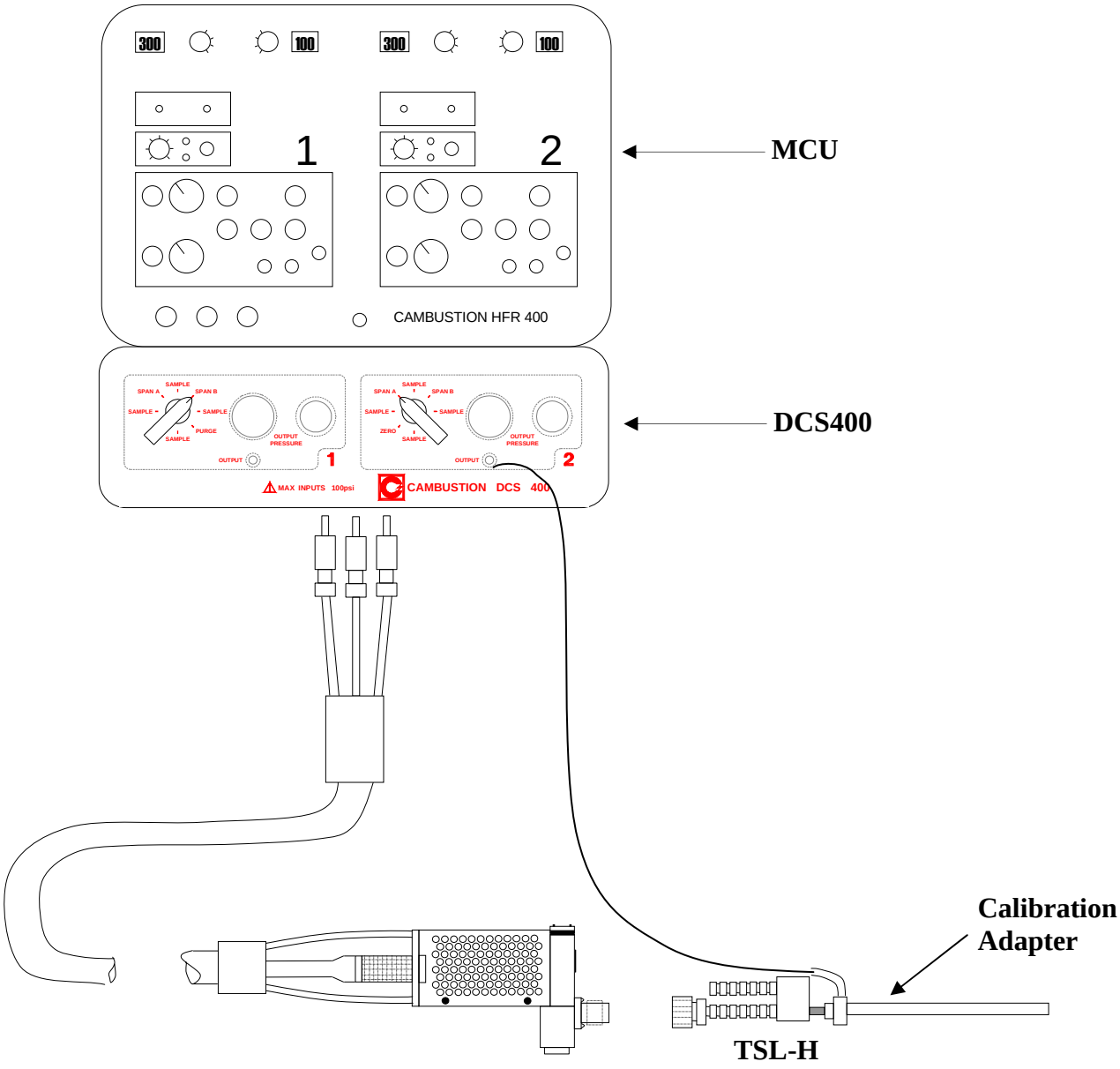


Figure A.2 - Schematic diagram of DCS

The purge setting is particularly useful if sampling is undertaken in an environment polluted by particulates (e.g. diesel or rich gasoline exhaust). When sampling is not required, the engine can remain running but the sample tube tip can be supplied with compressed shop air as a purge to prevent sample tube blockages.

The sample lines are cleaned in the conventional manner with cleaning wire.

A.3 Getting Started

A.3.1 Unpacking

The DCS400 system consists of:

One two-channel DCS400 control unit

Calibration adapters/ exhaust fittings as ordered

Four Swagelock QC4 double shut-off connectors for purge air, zero air and span gas

One Rotameter

Contact Cambustion immediately if any of these components are missing from the delivery.

A.3.2 Setting Up

Place the DCS400 control unit directly beneath the HFR400 MCU. Connect the zero air, purge air and span supplies using the Swagelok connectors supplied to the DCS400 control unit.

NB: The maximum inlet pressure to the DCS system is 6 bar.
Do not apply gas pressures in excess of this value.

The user is responsible for the safe maintenance and connection of these pipes. The pressure to the CAL-APT is regulated by the DCS400 control box and may be adjusted if necessary using the regulators mounted on the front panel of the DCS400. Sufficient gas should be applied to the sample capillary tip to completely exclude sample gas when calibrating or purging. The factory setting of approximately 2 bar is sufficient for normal exhaust port sampling situations this is discussed fully in “Operating Principles” (Section A.4).

A.3.3 Calibration Sample Line Adapter (CAL-APT)

The adapter (Figure A.1) should be slipped over the sampling end of the TSL-H and pushed fully home until the tip of the sampling tube is against the end cap of the CAL-APT. The compression nut should then be tightened to fix the TSL-H in position. The 1/8” Swagelok fitting at the other end of the clear 1/8” PTFE pipe should then be connected to the appropriate “OUTPUT” channel of the DCS400 front panel.

A.3.4 Engine Modifications

The outside diameter of the CAL-APT is 3/16”. A suitable compression fitting with a male ¼” NPT taper thread is supplied for fitting to the engine at the desired sampling location. This fitting is required to hold the sample line steady with the engine running and the ferrules need not be swaged onto the outside of the CAL-APT. Copper ferrules are supplied in the 3/16”

compression fitting supplied which allow the sampling location in the exhaust to be adjusted as required.

A.3.5 Testing Initial DCS Operation

Switch on the vacuum pump. Fit the TSL-H into the CAL-APT as described above and connect the heated sample line to the sampling head. By turning the selector switch on the appropriate DCS400 channel, all input gases may be admitted to the tip of the CAL-APT. Outward gas flow should be obvious. When the DCS400 selector is set to “SAMPLE” the flow should be inwards.

When the selector is set to any pressurised gas, pressure gauge on for the required channel on the front panel of the DCS400 control unit should indicate the pressure of the gas supplied to the CAL-APT. When the selector is set to “SAMPLE” the gauge will read zero.

A.4 Operating Principles

The Dynamic Calibration System conveys span, zero or purge air to the sample tube tip as shown in Figure A.2. The CAL-APT has been designed to allow a limited flow of gas to pass between the outer sheath and the inner sample tube by way of an annulus. The tip of the sample tube is slightly retracted into the outer tube to allow a small volume reservoir of the desired gas to cover the sample tube tip (Figure A.3). In this way, the gas at the sample tube tip is subject to the pressure and temperature fluctuations of the surrounding environment.

The flow rate of gas down the annulus can be controlled to minimise span gas usage, via pressure regulators mounted on the front panel of the DCS400 control unit. The gas is delivered to the CAL-APT from the DCS400 control unit by a 10m length of 1/8” PTFE pipe ducted inside the umbilical conduit.

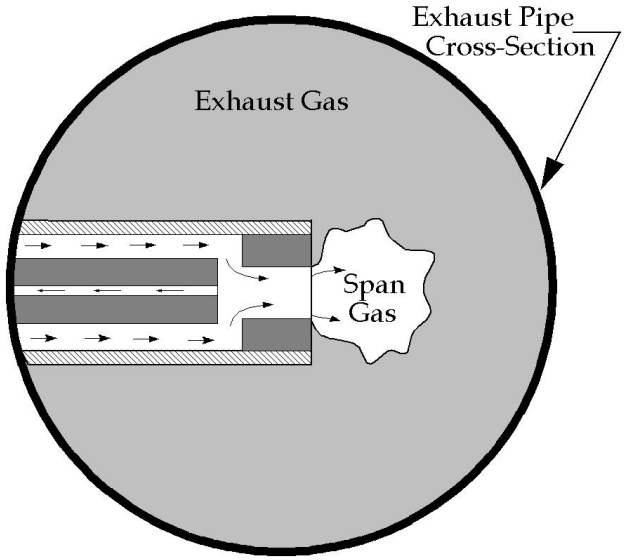


Figure A.3 - Diagram of sample tube tip during ‘Purge/Span/Zero’ operation

When “SAMPLE” is selected, a restricted vacuum (supplied from the vacuum pump) is applied to the annulus (shown in Figure A.4). This results in flow along both the annulus and

the sample capillary. The excess flow along the annulus ensures that no span gas remaining in the annulus contaminates the sample gas signal and maintains the frequency response of the system by purging the small extra volume at the end of the sample line.

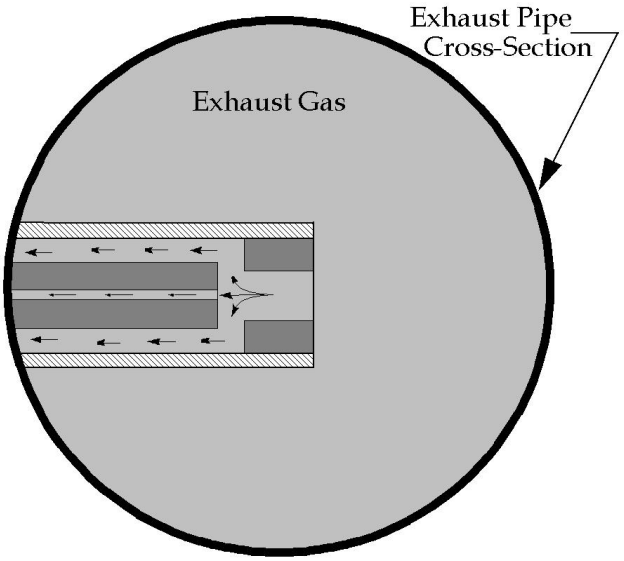


Figure A.4 - Diagram of sample tube tip during "SAMPLE" operation

The flow rates from the CAL-APT into the exhaust when spanning or purging are approximately 4l/min at a purge pressure of 2.0 bar. If air is used, then some interference with downstream gas and AFR sensors will occur, depending of course on the exhaust gas flow rate. In most cases, we anticipate negligible interference but alternative (e.g. inert balance) span and/or purge gases may be preferred in some cases.

A.5 Dynamic Engine Calibration

A.5.1 Preparing to Start

The following instructions refer to either channel.

Ensure that all connections to the DCS400 and to the CAL-APTs are sound and check that no plastic pipes are near hot engine surfaces. This is particularly important concerning the 1/8" PTFE pipes to the CAL-APT which must be secured well away from the exhaust manifold for exhaust port sampling work.

Set up the HFR400 system as described in the Section 3 of this manual. Locate the TSL-H/ CAL-APT assembly in the exhaust through the compression fitting at the desired sampling location.

Turn the selector switch on the front panel of the DCS400 unit (Figure A.2) to PURGE for the channel being used. Care should be exercised when sampling behind the exhaust valve as the positioning of the sampling tube tip too close to the exhaust valve may cause interference and damage to the engine and sampling tube.

A.5.2 Dynamic Calibration

Start the engine and stabilise to the desired operating conditions. Purging during the start-up will prevent blockage of the sample capillaries caused by enrichment and liquid fuel droplets.

Switch the DCS400 selector to SPAN and a flat response should be obtained with the engine running. This indicates that the sampling system is effectively isolating the signal from the exhaust pressure fluctuations. The settings of the CP VAC and FID VAC displayed on the main control unit should be steady.

For cold start applications, it may be necessary to provide a static calibration (with the engine off) before performing the experiment. A dynamic calibration may then be obtained after the cold data has been collected.

Once a flat response has been achieved, the signal voltage can be adjusted to a convenient value (e.g. 4V = 4000ppm C_3) by adjusting the SPAN screw on the MCU front panel.

Set the selector switch on the DCS400 to ZERO. A flat response of approximately 0V should be visible on the MCU panel meter and on your oscilloscope. Adjust if necessary using the OFFSET screw on the MCU front panel to zero the indicated signal. Re-span if an offset has required trimming.

If the zero signal is being contaminated by exhaust gas, the signal will appear periodically uneven. In this case, more ZERO gas is required at the sample capillary tip and the pressure of the ZERO, SPAN and PURGE gases should be increased using the regulators and gauges on the front panel of the DCS400 control unit until the response becomes flat. Do not, however, attempt to increase the gas input pressure to the DCS400 to above 6 bar—contact Cambustion for help.

A.5.3 Taking Measurements

With ZERO and SPAN both set, turn the selector back to PURGE until measurements are required. When you are ready, turn the selector switch to SAMPLE and, after a few seconds, an accurate, pressure-free signal will appear on the display of your data acquisition system.

The simplicity of the system allows rapid re-checking of the calibration whenever required and changes in operating temperatures of the engine at different conditions and their effect on the signal may be adjusted for accordingly.

A.6 Maintenance

A.6.1 Heated sample tube seal leaks

These are typically indicated by high frequency noise components on the signal (at frequencies higher than around 200Hz).

Ensure the Viton seal at the HSM end of the TSL-H is sound and that the terminator is tightened before fitting to the CP chamber.

A.6.2 Cleaning the Sample Tube

Allow at least 15 minutes for the sample tube and calibration fitting to cool outside the engine before attempting to handle. Leaving the DCS400 control unit set to PURGE will help reduce the cool-down time. Clean the sample tube from the CP chamber end.

A.6.3 Pipes and Fittings

Regularly inspect the polythene and PTFE pipes for signs of heat damage from hot engine surfaces. Ensure that all compression fitting joins remain tight and are properly connected to the CAL-APT and the DCS400 control unit.

A.6.4 DCS400 Vacuum Flow

Periodically test the bypass vacuum flow on both channels, using the rotameter assembly supplied. To connect the rotameter to the bypass restrictor, disconnect the 1/8” PTFE pipe from the Swagelock fitting in the 6mm ‘Y’-piece in the black nylon CP VAC pipe, and connect the top of the rotameter in its place.

If the flow is less than 500cc/min, the restrictor must be removed and cleaned using the 0.015” cleaning wire provided in the toolkit.

Contact Cambustion for all repairs or advice on installation.

A.7 Troubleshooting

This section deals only with problems that may arise relating solely to the DCS400 and the CAL-APT. Operating difficulties concerning the use of the HFR400 are dealt with in the “Troubleshooting” section of the manual. It is important that the HFR400 is operating correctly before attempting to trace faults to the DCS400 system.

A.7.1 No Calibration Signal

Check the connections of pipe work into the DCS400. Check that the channel FID is lit. Check that the selector switch on the DCS is set to the appropriate gas. Check that pressure gauge is showing that pressurised gas is available.

A.7.2 Unacceptable Level of Pressure-Signal Interference During Calibration

Check that there is sufficient supply of span gas to the DCS400. Increase delivery pressure of span gas to the CAL-APT by adjusting the pressure using the regulator on the DCS400. Do not increase the supply pressure of gas to the DCS400 above 6 bar.

For help with these or other problems, contact Cambustion.

B Line Heater Controller (LHC) Manual

B.1 Introduction

This section provides information on the operation of the Cambustion heated sampling system.

B.1.1 Overview

The Line Heater Controller (LHC) and Heated Transfer Sample Lines (TSL-H) are intended for situations where the sample is likely to contain liquid at ambient conditions. Without the use of a heated sample line, the hydrocarbons may condense into droplets during passage to the sample head. These droplets may smear down the internal walls of the sample capillary and produce erroneous signals. They are also unable to make the 90° turn required of the sample at the FID tube entry and are thus unrecorded.

The sample line is heated ohmically by a low voltage, phase-angle triggered AC supply, controlled by a PID system to achieve the desired operating temperature.

The PID parameters used by the controller have been pre-set and will provide adequate control of the line temperature for standard applications.

B.1.2 TSL-H

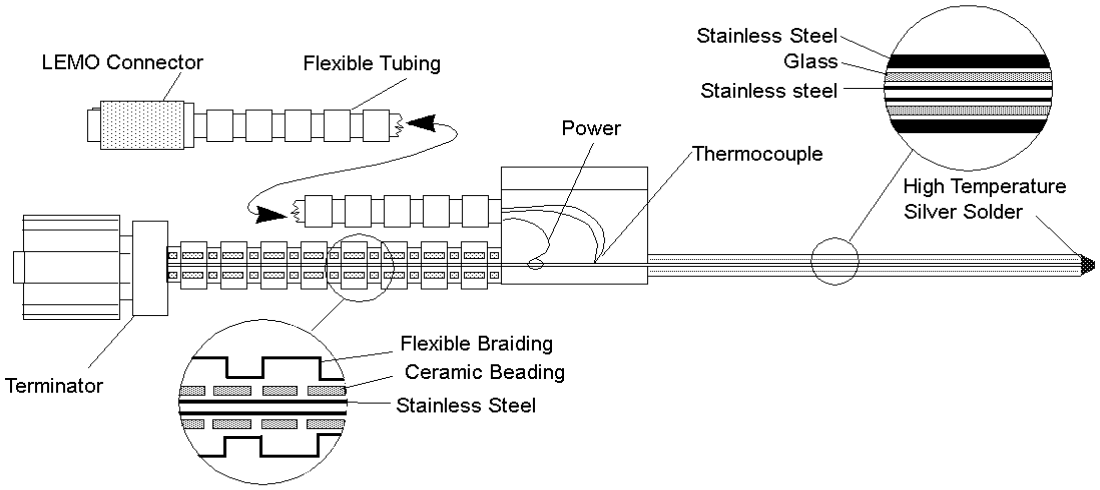


Figure B.1 - Construction of heated sample line

Figure B.1 shows a section through the TSL-H. It consists of a single central piece of stainless steel capillary insulated from the casing by glass or ceramic beading. The low voltage AC is applied through an anaconda conduit to the centre of the capillary via a connecting block. The current flows to earth at each end via connections to the casing. The insulation will survive tube temperatures of over 400°C. However, at these temperatures, the lifetime of the sample line will be significantly reduced. For standard gasoline applications a temperature of 150°C will be sufficient. The power and thermocouple connections increase

the thermal mass of the capillary at that point. Hence the measured temperature will be significantly lower than that at other parts of the tube. The construction of the tip is now by electron-beam welding so the gas temperatures endurable have been increased to the melting point of the stainless steel from which the casing and capillary are made.

B.1.3 LHC

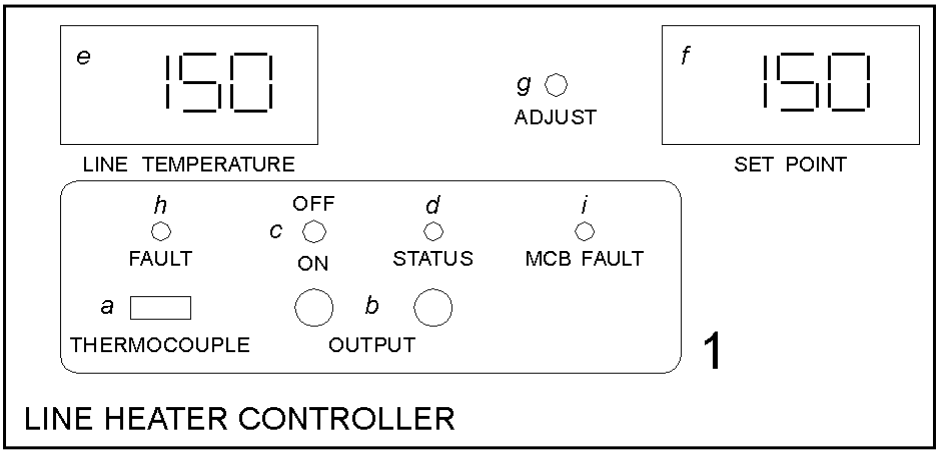


Figure B.2 - LHC display

One channel of the LHC is shown in Figure B.2. The thermocouple reading from the TSL-H is connected at (*a*) and the power is output via 4mm banana-type plugs at (*b*). There is an ON/OFF switch (*c*), which has an associated 3 colour STATUS LED (*d*) with the following meanings:

Colour	Meaning
Off	**Off**
Yellow	**On-Line under temperature**
Green	**On-Line at set point ±2 °C**
Red	**On-Line over temperature**

The line temperature is shown on the left panel meter (*e*) and the set point or desired temperature is displayed on the right (*f*). The set point can be adjusted by using the potentiometer (*g*).

Any fault with the thermocouple circuit will be shown by illumination of the FAULT LED (*h*).

There are two fault detection systems for the power parts of the circuit. The TSL-H should heat up very quickly (within a few seconds). Therefore, if the line does not reach temperature within 15 seconds, there is an audible warning and the power circuit is disabled. A warning will also sound if excessive external heating from the sampling location (i.e. the hot engine

exhaust stream) maintains the thermocouple junction at a higher temperature than the set point. Adjusting the set point may resolve this issue if appropriate.

To prevent damage from accidental short-circuiting of the output, the LHC is fitted with a miniature circuit breaker (MCB) which can be found on the rear panel. If this operates, the MCB LED (*i*) on the front panel will illuminate. Section B.3 contains details of fault diagnostics.

B.2 Operation

B.2.1 Power

There is a supply voltage selector switch on the rear panel. Check that this is set correctly for your supply. The user is responsible for the safe connection of the AC mains lead. Do not turn on the LHC at this stage.

B.2.2 Connections

A clip is fitted to the bulkhead of the sample head to provide support for the LEMO connector on the power lead of the TSL-H. The TSL-H should be connected to the sample head. Take care to align the TSL-H accurately with the sample head or damage to the central capillary will result – a finger tight seal is sufficient. Place the TSL-H power lead into the clip attached to the rear bulkhead.

With power disconnected, plug the connecting cable into the LHC. There are 3 connections—thermocouple and 2 outputs that are colour coded red and black.

Attached to the TSL-H there is a single LEMO connector, which should be coupled to the LEMO end of the LHC cable.

Check that the ON/OFF switch (*c*, Figure B.2) is in the OFF position. Power up the LHC. The two panel meters will illuminate and a short ‘bleep’ will sound. The line temperature displayed should be approximately ambient and the set point will be that chosen by Cambustion.

If necessary adjust the set point using a screwdriver. A set point of 150°C is sufficient for most applications.

Check that neither fault LED is illuminated – if not see Section B.3.

Turn the ON/OFF switch to ON. The status LED will illuminate yellow and the line temperature should begin to rise very quickly. There will be some overshoot (with the LED changing colour to red) but this will only last for a few seconds. The temperature should quickly stabilise at the set point and the LED will turn green. If any problems are encountered turn the ON/OFF switch to OFF and consult Section B.3.

B.2.3 Flow considerations

The method by which the line is heated and the temperature measured means that the indicated line temperature is an underestimate of the actual line temperature. This can have

important implications regarding CP and ΔP settings. Heating the sample gas increases its viscosity, hence the flow along the TSL-H is significantly reduced when the line is heated. In extreme circumstances this may lead to drop-outs in the signal as the TSL-H flow is not sufficient to supply the FID tube flow. Also, the lower sample flow into the CP chamber with heated lines means that the overall system vacuum capacity is somewhat improved.

B.3 Troubleshooting

B.3.1 Thermocouple fault LED illuminates

Switch the ON/OFF switch (*c*, Figure B.2) to OFF. Check that all thermocouple connections are correct at the LHC and TSL-H. If the fault light is still illuminated this suggests that the thermocouple is broken and the TSL-H should be returned to Cambustion for repair. This can be confirmed by changing the TSL-H with a second one if available. If two channels are available the fault may be attributed to channel/ cable/TSL-H by a process of exchanges.

B.3.2 Warning buzzer sounds

If the line temperature does not stabilise within 15 seconds this suggests that there is a connection problem. The power to the TSL-H is automatically switched off in order to prevent any damage to the line and a warning will sound. To silence the buzzer, switch the ON/OFF switch (*c*, Figure B.2) to OFF. The buzzer will also sound if the TSL-H thermocouple junction is externally heated by the engine exhaust, to a temperature higher than the set point. This can be remedied by increasing the set point.

If the temperature does not rise at all check that the MCB FAULT LED is not illuminated. Check all the connections and the MCB switches on the rear panel of the unit. If this does not resolve the problem, contact Cambustion for help.

If the temperature rises very slowly, check all connections. If all connections are sound, the thermocouple may have become detached from the central capillary. In this case do not use the TSL-H. Contact Cambustion for help.

There may be circumstances where the system is operating normally but the desired temperature cannot be reached in 15 seconds. To cater for this it is possible to extend (or eliminate) the warning period by a simple modification. Contact Cambustion for details.

B.3.3 MCB fault light illuminates

The miniature circuit breaker protects the internal transformers in the event of a short circuit at the output stage. Switch the ON/OFF switch (*c*, Figure B.2) to OFF. Check the connections and reset the MCB at the rear of the LHC. If this does not resolve the problem, contact Cambustion for help.

C In-cylinder sampling

This Quick User Guide is a supplement to the Main HFR400 Fast FID User Guide and the SSP User Guide. It is intended to indicate basic instrument settings for performing in-cylinder sampling via the SSP kit for normal engine operating conditions. Details of the sampling techniques, instrument tests and results interpretation can be found in the main body of the SSP User Guide.

The user is welcome and encouraged to discuss the in-cylinder technique with experts at Cambustion. This will avoid unnecessary frustration with badly configured sampling systems. On-site visits by a Cambustion engineer are also a valuable training aid and are available by request.

In short, this brief Quick User Guide summarises *what* to do. The SSP User Guide explains *why* to do it!

C.1 Quick User Guide

If the answer is "YES" to the following eight questions, it is appropriate to use this Quick manual.

1. Is the user already familiar and practised at exhaust Fast FID sampling?

2. Is the engine four-stroke and gasoline or gaseous-fuelled?

3. Is the user only interested in the [HC] immediately prior to ignition or the residual gas concentration?

4. Is the user intending to use the SSP kit as supplied by Cambustion after consultation with a Cambustion engineer?

5. Are results only required at engine speeds of 2000RPM or less?

6. Is only one channel of Fast FID data required?

7. Is your Fast FID fuel pure hydrogen?

8. Is calibration gas of between 3% to 5% C_3 in nitrogen available ?

C.2 Simple Operating Procedure

1. Remove the brass plug from the CP chamber and connect a sealed, 1-litre vessel strong enough to withstand an internal vacuum of 400mmHg with an 1/8" BSP thread. The hole through this threaded fitting should be at least 6mm diameter. Cambustion can supply a suitable volume and fittings.

2. Fit the threaded TSL-H to the HSM (i.e. the Fast FID sampling head) and heat the TSL-H to 150°C.

3. Set CP VAC = 400mmHg, ΔP = 50mmHg.

4. Ensure TSL-H is fitted with 0.016” insert.

5. Light the HSM and allow to warm up over 45 minutes.

6. Fit the SSP in the engine.

7. Zero and calibrate the Fast FID allowing for a maximum output of 10V=60,000ppm C_3.

8. Switch off the TSL-H, allow it to cool, remove it from the HSM and fit it to the SSP in the engine.

9. Reconnect the TSL-H to the HSM, re-light the HSM (if necessary), switch on the TSL-H and reset the CP and ΔP values (if necessary).

10. Start the engine, run at 1500RPM, light load, λ=1 and collect data on a suitable fast data acquisition system.

11. Introduce about 5 consecutive misfires by disabling the spark and record data.

For a homogeneous charge engine, the data should be similar to that shown in Figure C.11 of the SSP User guide. In particular, check that it exhibits:

a) a flat peak just before burn down at flame arrival

b) a rapid burn down within 3 milliseconds

c) the peak level of the first misfire is the same level as the preceding burning cycle

d) subsequent misfires at higher peak levels reaching 40,000 - 45,000ppm C_3 (for a stoichiometric fuelling strategy)

If these features are not present, contact Cambustion for assistance and advice.

C.3 Introduction to in-cylinder sampling

This manual provides instructions for the use of the Cambustion Sampling Spark Plug (SSP) kit. The SSP is intended for use with the Cambustion HFR400 Fast Response FID hydrocarbon detector to measure in-cylinder transient hydrocarbon concentration ([HC]) on a millisecond time-scale.

Applications include:

- Pre-flame mixture [HC]
- Study of residual gas content
- Post-flame HC motion within the cylinder
- Fuel injection/valve timing effects
- Development of stratified charge engines (both intake port injection and direct injection)
- Oil adsorption/desorption effects
- Out-gassing effect of various engine crevices

This manual is intended to be a supplement to the main HFR400 User Manual. It provides details on how to operate and maintain the SSP and also gives some indications on how to interpret in-cylinder results.

Before using the SSP for in-cylinder measurements, it is important to fully understand the fundamental operating principles of the HFR400. The most convenient method to ensure this is to begin with exhaust sampling which is fully described in the main user guide. In-cylinder [HC] measurement is not a routine procedure and interpretation of the data is more complicated than for exhaust sampling.

C.4 SSP Kit Accessory Components

The SSP kit (Figure C.1) contains all the components, which are required to make routine in-cylinder [HC] measurements with the HFR400.

The kit includes:

1 Sampling Spark Plug Body (to the customer's specifications)

2 Threaded, heated transfer sample lines of the required length

1 H-T Extension

2 Stainless steel capillary cleaning wires

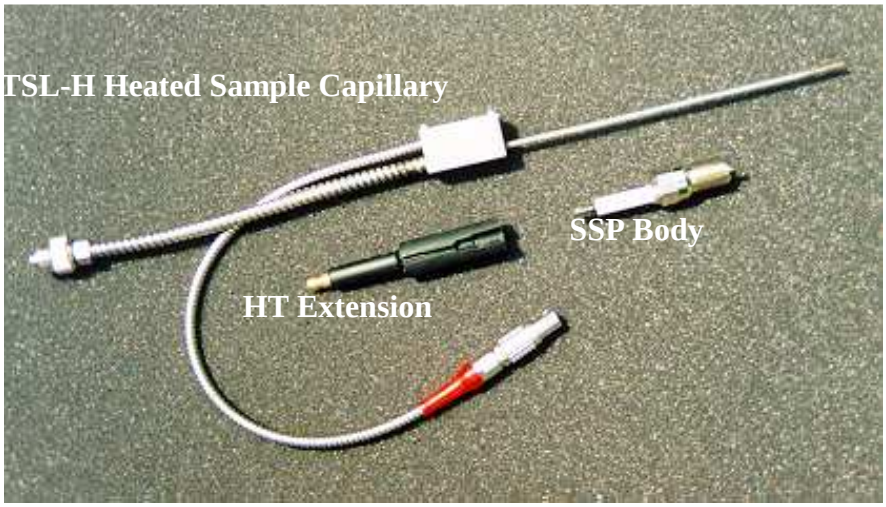


Figure C.1 SSP Kit

If any of these parts are missing from the kit on delivery, please contact Cambustion as soon as possible.

C.5 SSP Overview

C.5.1 SSP Body

The SSP is an offset spark plug (Figure C.2). This arrangement is often used to house pressure transducers or optical fibres for engine research applications. The FID system utilises the available access to accommodate a sampling capillary and the access hole is threaded for this purpose.

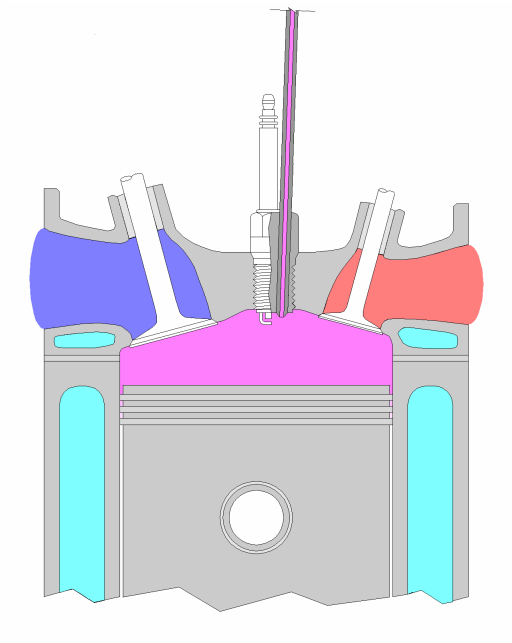


Figure C.2 SSP location in engine

The SSP is designed to operate like the standard spark plug and is ordered individually to have similar thread characteristics, electrode geometry and heat rating.

When assembled, the tip of the sampling capillary should be adjacent to the spark plug electrodes and therefore provides an accurate measure of the [HC] at this point just before the time of ignition. Figure C.3 shows a view of the tip of the SSP together with sample data taken with different engine fuelling.

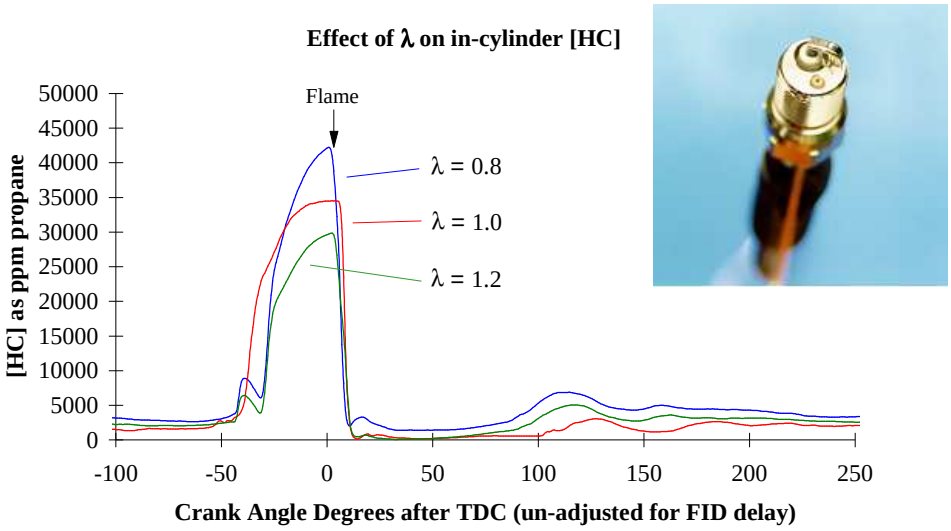


Figure C.3 Typical in-cylinder results

Interpretation of these signals is somewhat complex and is discussed further in Chapters C.7 to C.11.

C.5.2 Heated Sample Lines (TSL-H)

The threaded heated sample lines used for in-cylinder sampling may have a smaller inside diameter than those used for exhaust sampling. This is for two reasons:

1. To prevent pressurisation of the FID tube inlet (either due to raising of the CP chamber pressure or choking of the flow though the tee top).

2. To minimise the effect of removal of unburned gas from the vicinity of the spark plug on the engine performance.

The standard rigid penetration length of a TSL-H for exhaust sampling is around 150mm. Depending on the engine geometry (e.g. the spark plug recess) a slightly longer rigid section of TSL-H may be required for in-cylinder sampling. Design constraints mean that an extended rigid section requires a similar extension to the flexible section and lead to typical overall TSL-H lengths of around 330mm. The tip of the TSL-H is threaded to M3 for location into the SSP.

The base inside diameter of an in-cylinder TSL-H is 0.026”(0.65mm). Depending upon the application, this may then be fitted with a further tube insert to give a final internal diameter of 0.016 or 0.013” (0.4 or 0.33mm). The criteria for selection of the insert dimension are discussed in Section C.7.1 and the method for fitting/changing is outlined in Section C.5.2.2 & C.5.2.1.

The ideal combination of TSL-H length and insert diameter will provide sufficient flow to the HFR400 Hydrocarbon Sampling Module sampling head (HSM) to maximise period of valid signal per cycle, while protecting the FID tube inlet from pressurisation at peak flow. Experimental tests for verifying these qualities are explained in Section C.13.

C.5.2.1 Removal of TSL-H Inserts

The procedure for removal of the TSL-H insert is given below:

1. Unscrew threaded TNC assembly from the end of the TSL-H, and remove the TSL seal.

2. The insert may be pulled out of the TSL-H by gripping the exposed portion at the sampling head end with flat bladed pliers and pulling out of the assembly. Some inserts are soft soldered into the TSL-H at this end. If this is the case, a soldering iron should be applied to the sheath at this point to melt the solder whilst the insert is being pulled. If the above proves to be difficult, the TSL-H may be gripped in a vice (with soft jaws to avoid damage) and a sharpened needle file may be used to simultaneously push the insert at the engine end of the TSL-H.

C.5.2.2 Fitting of TSL-H Inserts

The procedure for fitting of the TSL-H insert is given below:

1. Unscrew threaded TNC assembly from the end of the TSL-H, and remove the TSL seal.

2. The insert length should be 2mm longer than the TSL-H sheath into which it is to be fitted.

3. The ends of the TSL-H sheath may be cleaned internally using a sharpened needle file if required.

4. The insert should be slid into the TSL-H sheath until it is flush at the engine end of the TSL-H. When fitted, the HSM end of the insert should protrude by 2-3mm from the sheath of the TSL-H.

5. If the insert is to be soldered into place (which is not normally necessary), stainless steel soft solder flux should be applied at the exposed joint between insert and sheath and a small amount of solder applied. Note that if solder is not applied, the interference fit between the insert and the sheath may be made tighter by slightly bending the insert prior to fitting.

C.5.3 High Tension Connection Extension

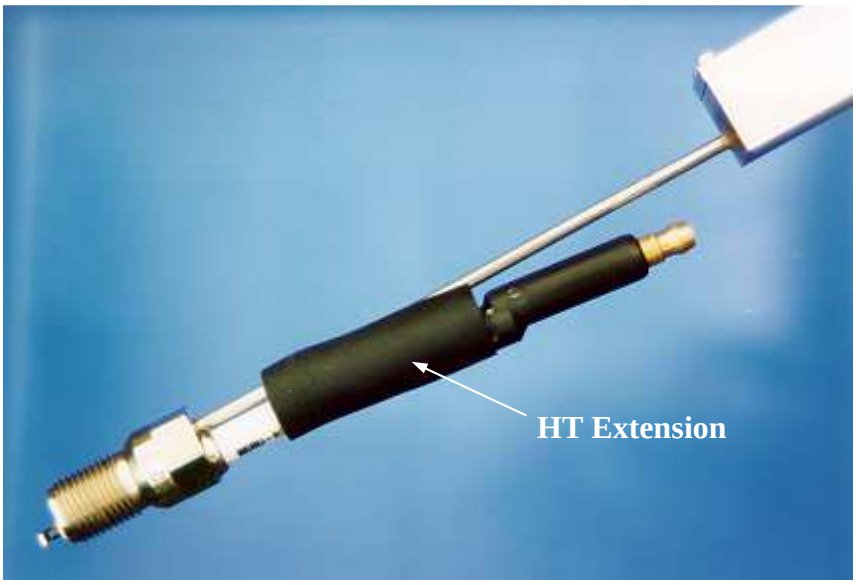


Figure C.4 SSP Kit Assembly

An H-T extension (Figure C.4) is supplied to extend the spark plug HT connection away from the TSL-H. With some engine designs, there is little room available for accessory equipment adjacent to the H-T lead in the spark plug recess in the cylinder head. The H-T extension allows the existing H-T lead to be connected to the SSP with the TSL-H in place.

C.6 Fitting the SSP Kit

C.6.1 SSP Body

The TSL-H is machined with a standard M3 thread (typically 16mm long). When fully inserted, the tip of the TSL-H sampling capillary should be adjacent to the spark plug electrodes. Note that if the TSL-H tip is recessed inside its M3 hole, then it will form a crevice, which may significantly affect the HC concentration measurement post-flame.

The following procedure should be followed for insertion of the SSP:

1. Screw the SSP into the cylinder head as one would fit a conventional spark plug (with the compression washer fitted for a flat seat plug). Please note that the ceramic surrounding the central electrode is offset. A spark plug spanner, which does not stress the offset ceramic insulator, should be used.

2. Insert the TSL-H into the SSP body after it has been fitted to the engine. A small quantity of silicone grease should be applied to the thread about 2mm back from the tip of the TSL-H before it is screwed into the female M3 hole in the SSP body (take care that no silicon grease enters the TSL-H, as this will cause a blockage). Torque should be applied by hand to the TSL-H via the heater box enclosure, which separates the rigid and flexible sections. Be careful not to over-tighten the TSL-H as it may fracture under excessive torsion.

3. The TNC connector at the opposite end of the TSL-H may then be fitted to the HSM observing the same alignment precautions as apply to exhaust sampling capillaries.

4. The TSL-H power cable should then be connected to the LHC cable at the LEMO connector.

5. Set the TSL-H operating temperature to 150^{o}C on the LHC. This may be adjusted later if condensation is seen to be occurring as outlined in Section C.11.6. The SSP female hole should be cleaned of grease after the TSL-H is removed and before the next experiment to prevent capillary blockage.

6. The H-T extension fits onto the bare threaded live electrode at the top of the SSP (remove the threaded nipple if it is fitted). Fit the H-T extension to the electrode and press the rigid portion of the TSL-H into the slot.

7. The engine H-T lead may then be connected to the H-T extension.

C.7 Configuring the SSP Sampling System

C.7.1 Selecting the TSL-H Inside Diameter

There are several considerations when deciding on the internal diameter required for the TSL-H fitted to the SSP. These are listed below:

1. Removal of the sample must not seriously affect the operation of the engine. This problem is most serious at low speed, high load conditions.

2. The tee-top must not become choked at peak cylinder pressures.

3. For systems with the CP chamber fitted, the highest sample flows must not cause significant pressurisation of the CP chamber.

Each of these is discussed below.

In general, it is best to operate with the largest possible insert diameter since this corresponds to the best system time response and the valid portion of the signal is maximised (see Section C.9.2.1).

C.7.1.1 Sample Removal Effects

The effect of sample removal will depend upon the exact engine configuration and running conditions. The best method of establishing that the IMEP is not significantly affected is by examining any changes to cylinder pressure from an in-cylinder transducer. In practice, it can be inferred from engine smoothness etc.

The relatively short periods of time spent at pressures significantly above atmosphere mean that for a typical 500cc cylinder, the sample flow taken is substantially less than 1% of the cylinder contents - even for the highest sample flows associated with the largest inserts. Unless the engine to be studied runs at unusually low speed and/or has unusually small displacement, choking of the tee-top occurs before sample removal becomes problematic (see below).

Cambustion have conducted tests on a single cylinder engine at low speed (~1000rpm) and established that the lean misfire limit is not significantly affected by the fitting of an SSP with a heated TSL which is 360mm long with an ID of 0.026".

C.7.1.2 Choking of Tee-Top Exit

Choking of the tee-top exit occurs at some sample inlet pressure when the flow at that point becomes sonic (Mach No = 1). The table below shows the approximate sample pressures at which tee-top choking may occur. The data is generated from SATFLAP and assumes a 330mm long TSL-H, which is heated to 150^{o}C.

Table C.7.1.2 Maximum sample pressures (bar) for various sampling configurations

	CP Vacuum setting				
TSL -H ID	**400**	**300**	**200**	**100**	**0 (Atm.)**
0.016”	23	30	36	43	49
0.026”	6	9	11	13	15

The results shown above should be used for guidance only, but it is worth noting the following:

- Choking of the tee-top is due to the pressure *ratio* across it. Therefore, as the CP absolute pressure is reduced (CP VAC increased), choking occurs at lower sample pressures.

- Practically, choking is characterised by a sharp increase in the signal level at peak pressure (this is shown in Figure C.17). If the user is interested in the cylinder concentrations associated with the inlet and compression process, it will be necessary to run in a situation of low CP pressure where the tee-top may choke. In such a situation, the portion of the signal of interest (where cylinder pressure is relatively low) will still be valid and the portion where choking may occur should be disregarded as being invalid.

C.7.1.3 CP Chamber Pressurisation

CP chamber pressurisation may be eliminated by operation without the CP chamber fitted, or by fitting of an additional volume to the CP chamber (see Section C.13.2.1).

C.7.2 Selecting CP Chamber Configuration

There are two possible operating configurations for the FID when sampling from inside the engine cylinder.

1. Run the HSM with the CP chamber open to atmosphere.

2. CP chamber operated below atmospheric pressure with an extension volume fitted.

There are advantages and disadvantages associated with each configuration. The procedures associated with each mode of operation are described in Chapters C.8 and C.9.

C.7.2.1 CP Chamber Open to Atmosphere

Broadly speaking, the CP chamber open to atmosphere is a simpler configuration experimentally but may yield limited results.

The signals from this configuration will only be valid when the cylinder pressure is substantially above atmosphere. This means that the inlet process and the start of the compression stroke may not be observed. Problems with producing useful signals may also be encountered when running at higher engine speeds (above 2000 rpm) or with long sample tubes (more than 350mm TSL-H).

The configuration is easy to calibrate and establishing isolation of FID sample flow from cylinder pressure fluctuations is relatively simple.

C.7.2.2 CP Chamber Below Atmosphere

With the CP chamber run at a vacuum, the limits of engine operation for which the signals are valid are wider. There is also the possibility of some study of the intake and early compression process. However, there are additional difficulties in establishing sample pressure isolation from the engine signals and calibration is significantly more complex.

C.8 Operation with CP Chamber Open to Atmosphere

With this mode of operation, the CP chamber is vented to atmosphere. This can be done either by removing the brass plug in the base of the CP chamber, or by completely removing the CP chamber.

C.8.1 System Limitations

In this mode, the TSL-H flow will only carry sample from the engine to the HSM when the cylinder pressure is above atmospheric. This means that the signal is only valid during the latter part of the compression (depending on the inlet manifold vacuum) until approximately EVO. Indeed, during the inlet stroke and the start of compression, the flow in the TSL-H is reversed and sample for the FID tube is drawn from the gas residing near the exit of the tee top. This feature provides a useful means of calibration and is discussed in Section C.8.5.

C.8.2 System Hardware Modifications

When running with the CP chamber open to atmosphere the following hardware modifications should be made:

1. The CP VAC regulator on the MCU should be turned fully anti-clockwise in order to prevent the regulator from trying to regulate atmospheric pressure (the CP VAC reading on the MCU should read around zero).

2. In order to prevent the unnecessary loss of vacuum, the `push-in' tee connection at the rear of the HSM (connecting the 3 black vacuum pipes) should be removed. The short black pipe from the CP chamber vacuum restrictor should be left unconnected and the short black pipe from the FID chamber restrictor should be re-connected to the black vacuum supply pipe with a simple 6mm union.

C.8.3 Selection of TSL-H Inside Diameter

The inside diameter of the TSL-H should be selected using the guidelines given in Section C.7.1.

C.8.4 Selection of ΔP Setting

With the CP chamber open to atmosphere, the only selectable system vacuum setting on the MCU is ΔP.

A discussion of techniques for establishing the range of linearity, together with the issues peculiar to this CP configuration is given in Section C.12.

C.8.4.1 Recommended ΔP Setting

Experiments have been conducted at Cambustion with a hydrogen fuelled FID fitted with a standard 0.008" (0.2mm) tee piece, with a gas divider fed with zero air and 5% propane in nitrogen. These indicate that reasonable linearity of response is maintained for ΔP values up to 25mmHg for a tee-top exposed to atmospheric pressure.

In general, it has been found that running with the fuel supply slightly above the optimum level (increasing the fuel pressure by ~0.1 bar to give a signal of slightly less than the maximum) increases the range of linearity to higher concentration samples.

Clearly the greatly reduced values for ΔP means that any pressurisation of the FID tube inlet at high cylinder pressure is proportionately more serious with regard to sample flow. This means that experiments to establish sample flow independence from cylinder pressure are very important. These are discussed in section C.13.

C.8.4.2 Fuel Gas Selection

The range of linearity for a mixed fuel gas (H_2/He) is significantly reduced compared to the pure H_2 fuel gas. See Section C.12.1.2 for details.

C.8.5 In-Situ System Calibration with CP Chamber Open to Atmosphere

A significant advantage of operation with the tee-top at atmospheric pressure is the simplicity of calibrating the HFR400 system while the engine is running. This provides one calibration per engine cycle. It is achieved by utilising the reversed flow in the TSL-H during the period that the inlet is below atmospheric pressure (mainly during the engine intake stroke). During this period, gas from the vicinity of the tee-top exit is ingested back into the tee-top and hence up the FID tube to the flame.

If a gentle jet of span gas is introduced into this vicinity then, during periods of reversed flow, the FID tube samples pure span gas and a calibration may be made. This process is shown in Figure C.5.

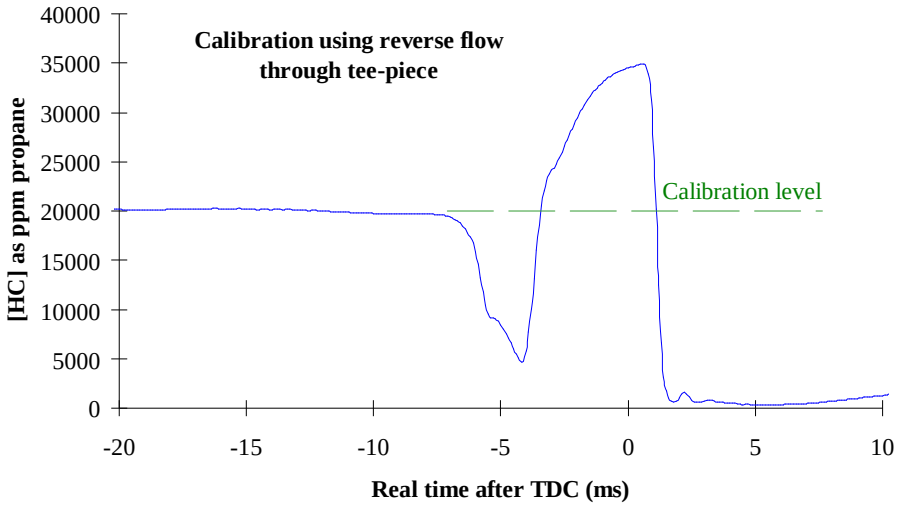


Figure C.5 Engine running calibration through the tee-piece

The span level obtained with this method will verify that the FID tube is clear. Note that this technique does not directly indicate blockages in the TSL-H as there is no flow of calibration gas through the TSL-H with this configuration. Such blockages will generally affect the shape of the engine-originated part of the signal and not the span level.

C.9 Operation with CP Chamber Below Atmospheric Pressure

With this mode of operation, the CP chamber is fitted in the standard exhaust sampling format. Note that it may be necessary to fit an increased volume to the base of the CP chamber (see Section C.13.2.1) and calibration may be facilitated by fitting of a special CP chamber (see Section C.9.4.2).

C.9.1 Selection of TSL-H Inside Diameter

The selection of the TSL-H inside diameter will depend upon the sampling pressures selected (see below). It should be chosen with reference to the guidelines given in Section C.7.1.

C.9.2 Selection of CP and ΔP Vacuums

C.9.2.1 CP Vacuum - Sample Flow Reversal Considerations

The large pressure fluctuations in the firing engine cylinder require careful choice of HSM vacuum values. During the intake stroke, the cylinder is at sub-atmospheric pressures and depending on the vacuums selected and the manifold depression, the flow may reverse in the TSL-H (in this situation, gas will flow into the TSL-H from the CP chamber towards the engine).

With the engine running, periods when this is occurring can be identified using an unlit butane gas lighter at the “TEST” port on the front of the MCU in the same way as drop-out is detected for exhaust sampling (see Section 7.1.3). In this case, the reverse flow portions of the signal will turn into high ppm peaks from the butane that is flooding the CP chamber. A typical signal demonstrating this action is shown in Figure C.6.

In the periods around flow stagnation in the TSL-H (where engine pressure is equal to exhaust pressure), the signal is not valid from the engine or for calibration purposes. During these periods, the length of the TSL-H must be purged of its gas mixture before the signal becomes valid again. Generally this will happen twice on every cycle. If TSL-H flow reversal can be prevented (by running with a CP vacuum sufficient to ensure continuous flow from the engine to the HSM throughout the engine cycle), then these periods of completely invalid signal can be eliminated which make signal interpretation simpler. Note that for normal engines this may only be possible when running under some load.

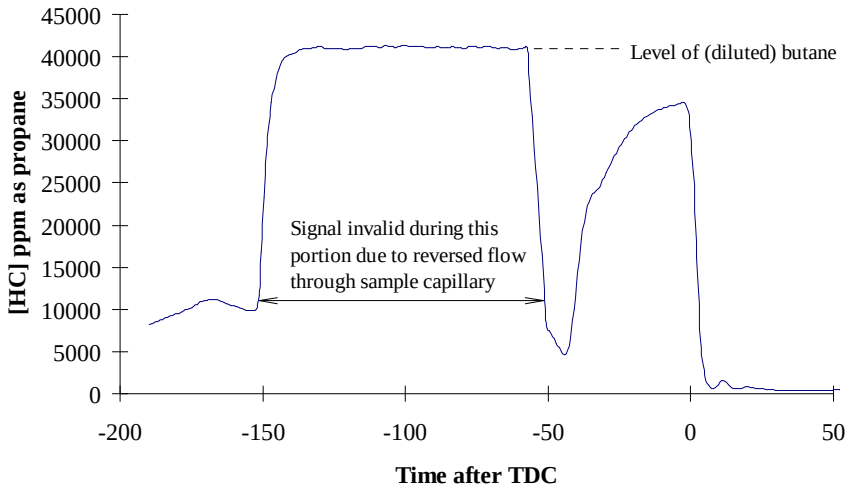


Figure C.6 Testing for signal validity via the MCU "TEST" port

In general, the invalid (reverse flow) sampling period can be reduced by increasing CP VAC. It should be remembered that the available vacuum capacity must be shared with the ΔP requirement and with another HSM (if fitted).

The periods of reverse flow can also be used for calibration purposes (see Section C.9.4.2).

C.9.2.2 CP Effects on Time Response and Signal Response

It should be noted that the CP vacuum setting affects the system response time - particularly at lower cylinder pressures (increasing CP vacuum level will improve system transit times and response times). SATFLAP may be used to evaluate these effects at a given steady sample inlet pressure.

CP vacuum also has a secondary effect on the sample mass flow by changing the density of gas at inlet to the FID tube. In general, a higher value of CP vacuum will lead to a reduced sample mass flow and therefore to a reduced level of signal output.

C.9.2.3 Recommended CP Vacuum Setting

A CP vacuum of 400mmHg has been found to give a useful in-cylinder signal under most circumstances. Operation at vacuums significantly higher than this may require system modifications to improve vacuum capacity - please contact Cambustion for advice.

Note that tee-top choking should also be considered. See Section C.7.1 for details.

C.9.3 Considerations for ΔP Selection

Changing ΔP has the following effects on the FID output signal:

1. Increasing ΔP generally improves the vacuum control system performance.

2. Increasing ΔP increases the FID sample flow (and hence signal response).

3. Increasing ΔP will increase the depletion rate of sample from the tee-top.

4. Increasing ΔP will marginally improve the system transit time and response time.

The implications of each of these is discussed in turn:

1. The value of ΔP required for a particular configuration depends upon the FID tube internal diameter selected in the tee piece. For reasons of vacuum control stability, it is desirable to operate with a ΔP value as high as possible. This leads to a requirement for as small a diameter of FID tube as practicable. For ease of handling and cleaning this means that Cambustion recommend an FID tube ID of 0.008" (0.2mm) for in-cylinder applications.

2. High sample flows into the FID can lead to a non-linear response of the instrument at high concentrations (which are typical of in-cylinder applications). It is important to establish that the instrument has a linear response in the range of concentrations of interest (see Section C.12).

3. Under conditions of low or negative flow in the TSL-H, sample can be drawn into the FID from the CP chamber causing signal drop-out.

4. The effect of ΔP on the overall response time of the system is very small. It is most unlikely that this effect will change the selection of ΔP.

C.9.3.1 Setting Fuel and Air Flows

The technique for setting the fuel and air flows to the FID is described in the HFR400 main user guide. In general, it has been found that running with a fuel flow slightly higher than that to give the highest signal level (corresponding to ~0.1 bar higher on the fuel pressure regulator) will tend to extend the high concentration limit of linearity to higher HC concentrations.

C.9.3.2 Recommended ΔP Setting Range

The considerations above associated with the vacuum capacity of standard system lead to a recommendation for ΔP of 30mmHg for a typical configuration (CP vac 400mmHg, FID tube 0.008").

Tests done with a typical installation (0.008" FID tube ID, H_2 fuel) indicate that for CP VAC settings of 300mmHg or greater, the response of the FID is reasonably linear up to 50,000ppm C_3 for values of ΔP up to about 30mmHg (+/- 2% from ideal). Note that fuelling with H_2/He may lead to a substantial reduction in this level (discussed in Section C.12.1.2) and the maximum level of ΔP is reduced to around 30mmHg.

C.9.4 System Calibration with CP Chamber Fitted

Unlike exhaust sampling applications, dynamic calibration such as that used for exhaust applications is not possible with the SSP due to the extremes of sample pressure. Also, the calibration technique described in Section C.8.5 is not possible with the standard CP chamber

configuration. The technique may be applied however, if a modified CP chamber is fitted. This is described in Section C.9.4.2.

C.9.4.1 Static Calibration - Simple Technique

It may be possible to flood the engine cylinder with span gas while the engine is stationary - either through the inlet, exhaust or through an auxiliary cylinder opening (e.g. pressure transducer tapping).

If the above is not possible, then the system should be calibrated outside the engine. This is described below.

1. Choose a suitable calibration gas for your application (ideally around half of the maximum concentration required to be measured). Zero gas is also required to indicate any signal offset.

2. Disconnect the TSL-H from the HSM and remove from the SSP (if fitted).

3. Fit the TSL-H to the HSM, switch on the LHC and re-light the FID (if it has gone out).

4. Flow a gentle quantity of span gas over the TSL-H tip. Be careful not to burn your hand on the hot TSL-H and HSM!

5. Set the output voltage to a suitable level for the span gas as outlined in the HFR400 main manual.

6. Confirm that zero levels are acceptable by using the zero gas in a similar way.

This method of calibration requires the TSL-H to be removed from the SSP in the engine. Unscrewing the TSL-H from the SSP requires the TSL-H to be disconnected from the HSM. This action is likely to extinguish the FID flame and re-lighting the flame can, in itself, produce some signal drift. This should be less than 5% but means that calibration using this method is not ideal and can only be used as an estimate. Settings of CP and ΔP vacuum should be checked and re-adjusted after re-connecting the TSL-H and re-lighting.

C.9.4.2 Calibration with Modified CP Bleed Configuration

Cambustion can supply a CP chamber, which is modified to admit the bleed flow directly over the exit of the tee top. This is shown in Figure C.7.

Both the CP and FID vacuums in the HFR400 system are regulated by bleeding atmospheric air into a volume which is evacuated by the vacuum pump via a fixed restrictor (details of this system are given in the main HFR400 user guide). In the standard CP configuration, this bleed flow is admitted though a hole into the top of the CP chamber and originates from the “TEST” port at the centre of the base of the front panel of the main control unit.

With the modified system, the bleed hole in the top of the CP chamber is sealed, and the bleed flow is admitted through a separate tube such that it exits over the end of the tee top. During normal operation this modification will have no effect on the operation of the system - merely changing the point of entry of bleed gas into the CP chamber.

However, if, during the engine cycle the flow reverses in the TSL-H, the FID tube samples gas which originates in the vicinity of the tee-top exit (this principle is used to calibrate the in-cylinder sampling system without the CP chamber fitted - see Section C.8.5). With the modified CP bleed configuration, this gas is the bleed gas that originates at the MCU "TEST" port. If this bleed gas is caused to be pure span gas, then a calibration level may be obtained on every cycle in the same way as described in Section C.8.5.

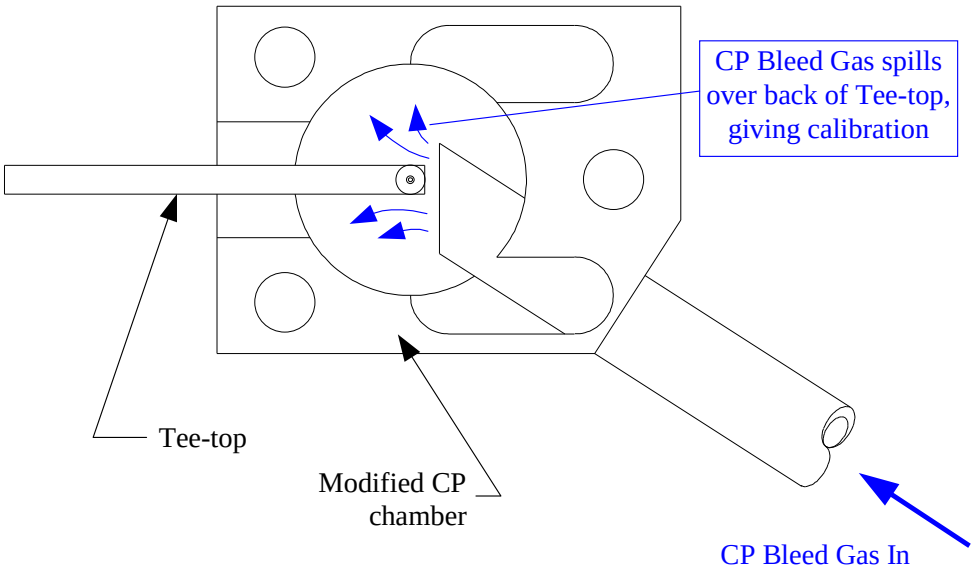


Figure C.7 - CP chamber modified for in-situ calibration.

The "TEST" port gas can be made to be either pure span or pure zero gas by fitting a short stub of 6mm OD pipe into the fitting (the port is actually a bulkhead 6mm pipe union with O rings fitted). Over this stub of pipe should be placed a pipe of slightly larger diameter from which is issuing a gentle jet of the required span/zero gas. The flow of this gas must be set such that there is a small excess of gas issuing to atmosphere down the annulus formed between the pipes. Note that the pipes must be a very loose fit over each other or else the "TEST" port will be pressurised and the vacuum control system will not operate correctly. This configuration is illustrated in Figure C.8.

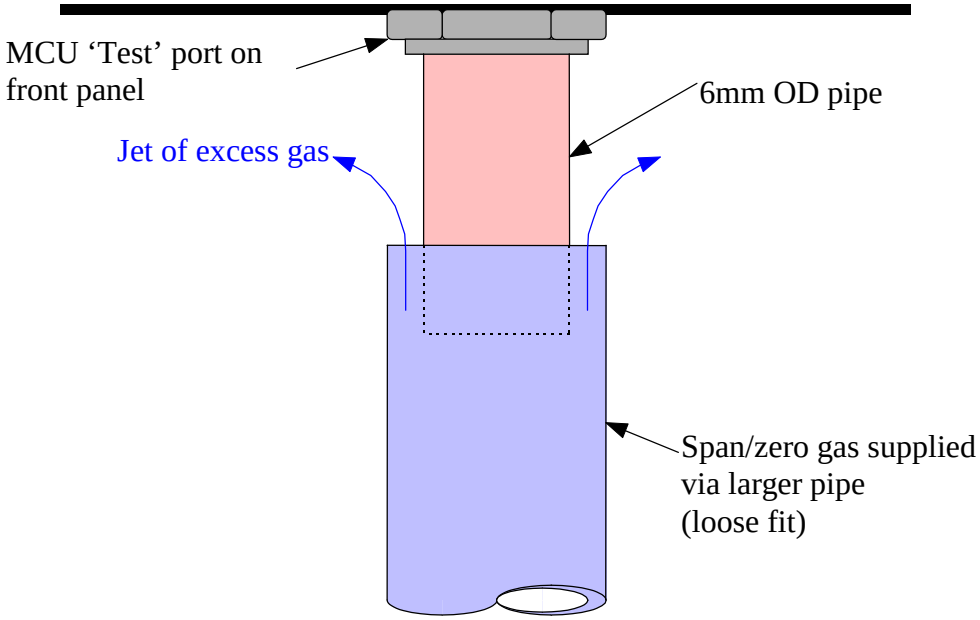


Figure C.8 - Span/Zero gas supply connection to MCU "TEST" port.

If the engine condition being tested is such that there is no reversal of flow in the TSL-H during the cycle (i.e. absolute inlet manifold pressure is always above CP chamber pressure - this can happen at low CP chamber pressures and/or high engine loads), then the flow in tee top is always out of the exit and the bleed gas cannot enter the FID tube. In order to provide a calibration in this situation, the engine load should be reduced in order to force flow reversal in the TSL-H. The optimum engine condition for minimum inlet manifold absolute pressure is idle.

Note that the bleed flow with very high CP chamber vacuum levels can be rather low and it can take around 15-20 seconds for gas introduced at the "TEST" port to arrive at the sampling head (particularly if an extension cable is fitted). In the case where the CP vacuum is set at its lowest absolute pressure level, the bleed flow is zero and in this case the CP chamber restrictor will need adjustment - please contact Cambustion for details.

C.9.5 Sample Pressure Independence Validation

The issues surrounding the independence of the FID signal from sample pressure fluctuations are discussed in Section C.12.

It is not possible using the SSP to verify pressure isolation using the dynamic calibration method available in engine exhaust locations. However, there is an alternative method of validation, which relies on the assumption that a homogeneous mixture of unburned fuel and air exists near the sampling location throughout the compression and expansions strokes during a motoring cycle.

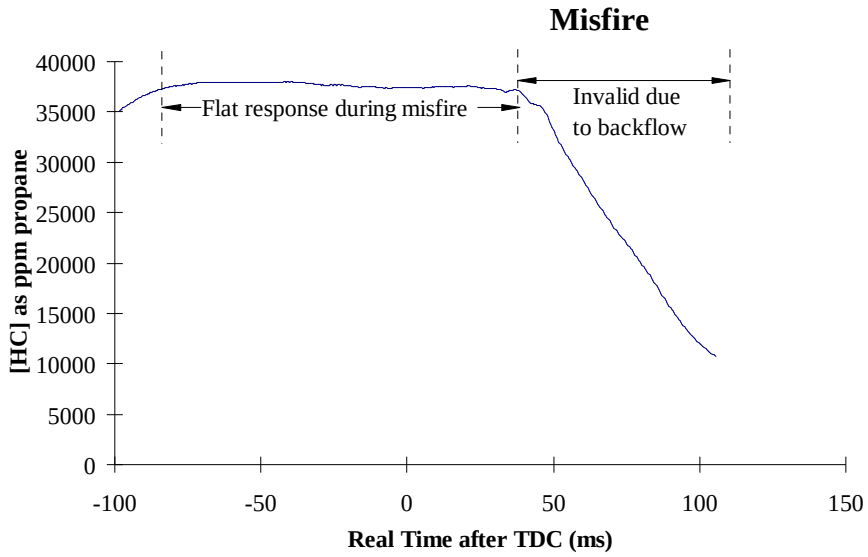


Figure C.9 - Checking signal pressure independence during a fuelled motoring cycle

Figure C.9 is a signal from an SSP fitted to a gasoline fuelled engine with the spark disabled.

If the signal is independent of cylinder pressure then either side of Top Dead Centre (firing TDC), it should display a generally flat level.

The most useful cycle to examine for this effect is the first misfire following the firing cycles. With a liquid fuelled engine as the cylinder cools down, it is possible that significant quantities of liquid fuel in the engine cylinder will, invalidate the assumption about complete charge homogeneity around TDC compression. The experiment should be performed when the engine is fully warm and the misfires limited to a few cycles only. This will minimise condensation of liquid fuel and droplet ingestion, which may lead to capillary blockage and substantial drift problems.

C.10 System Time Response Evaluation

It is very difficult to demonstrate the frequency response of the FID fitted with an SSP at sample pressures above atmosphere. Clearly the transit time through the system and the time constant are strongly dependent on the sample pressure itself. SATFLAP may be used to give a general idea of the change in transit time and time response as a function of sample pressure.

The rapid change in sample gas concentration associated with the flame travelling across the tip of the TSL-H gives an opportunity of measuring the system time response at this point. Figure C.10 shows the flame arrival of a typical signal expanded to measure the time response.

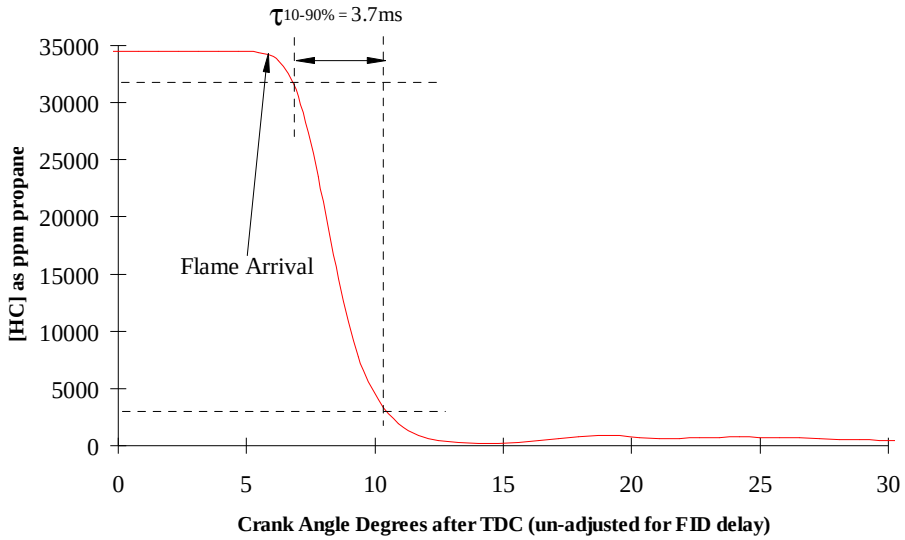


Figure C.10 - Checking time response from flame arrival signal

With the standard sampling system and set-up, the 90-10% burn-down transient should be no slower than about 4ms. Interpretation of the signals is discussed in SectionC.11.

C.11 Interpretation of In-Cylinder Signals

C.11.1 General

As previously stated in the Introduction, in-cylinder sampling is more difficult than exhaust sampling. Both the operation and signal interpretation require careful consideration for the reasons outlined below:

1. When studying data on crank angle time-scales, in-depth knowledge of the engine's gas exchange processes is required.

2. The sample pressure fluctuations result in a transit time distortion due to unsteady flow through the TSL-H.

3. There is potential for flow reversal in the TSL-H.

4. There are significant changes to the flow regime in the TSL-H and tee-top during a single engine cycle.

5. In-cylinder results are subject to cyclic variability.

With in-cylinder sampling, it is very easy to produce signals which for one reason or another are not valid (or can be misinterpreted). Wherever possible, opportunities to validate the various aspects of the in-cylinder signals should be taken.

This section will discuss results from various sampling situations. If results are obtained from similar engine conditions that do not resemble the traces illustrated here, the reader may wish to consult Cambustion directly.

The results discussed below are taken from an SSP in a 4-Stroke port-fuelled engine.

C.11.2 Low Speed, Low Load

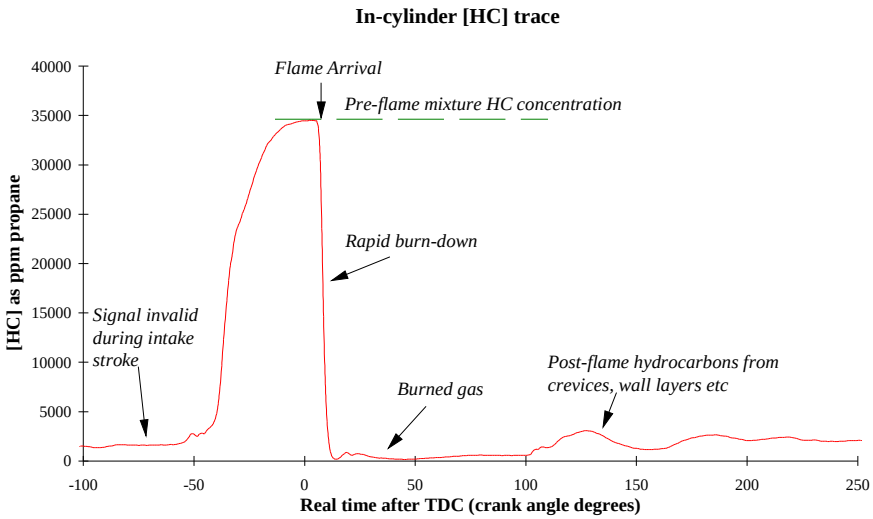


Figure C.11 - Typical in-cylinder trace with features

Figure C.11 illustrates the noteworthy features of a typical in-cylinder [HC] signal from an SSP. It exhibits a fast burn-down transient as the flame traverses the TSL-H capillary tip and a flat pre-flame mixture concentration. Post-flame hydrocarbons can be seen approaching the TSL-H tip during the exhaust stroke.

Time-axis distortion (not shown here) will be discussed in Section C.11.7.

C.11.3 Effect of Increased Engine Speed

Figure C.12 illustrates the effect of increased engine speed on the in-cylinder [HC] trace.

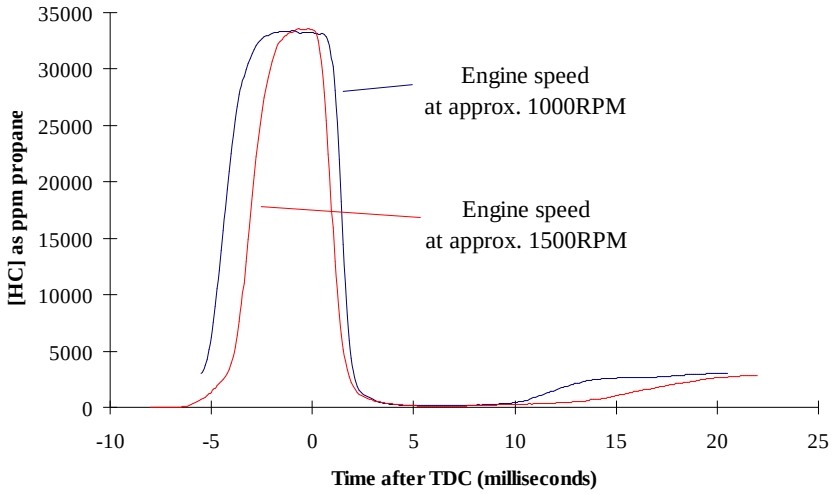


Figure C.12 - Effect of increasing engine speed on signal

The reduction in time available for pre-flame sample to enter the FID flame at high engine speed causes an apparent ‘shortening’ of the FID signal.

If the pre-flame mixture concentration is the subject of study, this reduction of the pre-flame interval is significant. At speeds above a particular threshold, the pre-flame mixture concentration will not be properly resolved before the drop associated with the flame itself (the signal will still be rising towards the plateau value). This problem can be alleviated to some extent by retarding the spark (if appropriate) which delays the flame traverse over the TSL-H tip.

The speed threshold for valid pre-flame signals can be established by introducing misfires (akin to very greatly retarded spark timing and allowing the maximum signal settling time) and ensuring that the pre-spark concentration is the same as the peak concentration in the first following misfire.

If pre-spark [HC] measurements are to be made at speeds higher than this threshold, then the engine must be run up to the condition of interest and skip fired. The first misfiring cycle of the engine will indicate the pre-spark mixture concentration. This process should be repeated several times if statistical information about this feature is required.

Note that misfires following the first will not give representative pre-flame concentrations because of the reducing residual gas fraction.

C.11.4 Effect of Increased Engine Load

The speed threshold at which the pre-spark [HC] is valid also changes with engine load. The faster increase in cylinder pressure as load in increased means that the engine-originated signal becomes valid sooner (essentially extending the pre-flame plateau to the left). This makes valid pre-spark [HC] measurement feasible at higher speeds as load is increased.

C.11.5 Cyclic Variability

The results from 4 successive firing cycles at idle are illustrated in Figure C.13. The average is plotted with a bold line. Note that both the flame arrival time and the pre-flame [HC] concentration exhibits cyclic variability. It is important to decide on an appropriate method of data presentation depending on the application remembering that a single partial burn or misfire may greatly affect a signal average.

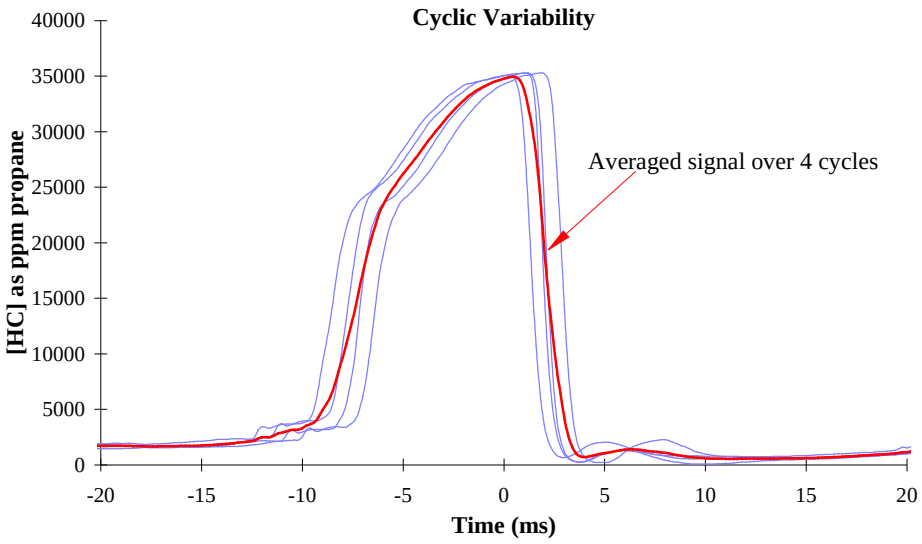


Figure C.13 - Cyclic variability

C.11.6 Deposition of Liquid Fuel

When sampling from the cylinder of a liquid-fuelled engine, it is possible that some liquid is deposited on the internal walls of the TSL-H capillary. This may result from non-vaporised fuel droplets entering the sampling system or the condensation of liquid fuel from the sample gas. Figure C.14 shows a signal, which is typical of this situation.

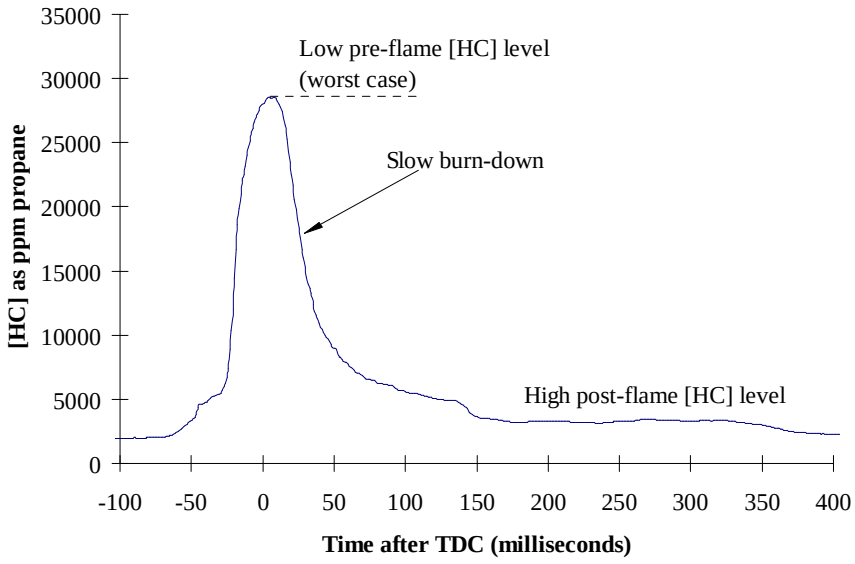


Figure C.14 - Example of liquid fuel signal contamination

The typical features of this trace are:

1. An apparently low pre-flame [HC] caused by poor fuel vaporisation.

2. A slow burn-down - caused by evaporation of residual fuel in the sampling system.

3. A higher than normal post-flame [HC] level.

Operating the TSL-H at 150°C is usually effective at preventing these problems but the temperature may have to be increased if smearing of the signal is apparent (possibly in situations where the fuel is made up of heavier fractions - summer fuel).

Signals such as the one shown in Figure C.14 may also indicate malfunction of the TSL-H itself - refer to the HFR400 main user guide for advice.

C.11.7 Time Axis Distortion

The speed at which gas travels through a capillary depends upon the pressure difference at either end that is driving the flow. Generally, as the pressure difference increases, both the transit time and time constant decrease. Details of the theory relating to this are found in the HFR400 main user manual.

As well as knowing which portions of the in-cylinder signals are valid and originate from the engine, it may also be very important to be able to identify the crank angle at which the gas entered the TSL-H tip so that the results may be compared with specific engine crank angle related events like spark, TDC or EVO.

Unfortunately, throughout the engine cycle, the sample pressure is varying significantly. For example, at peak pressure the signal delay may be 2ms whereas after EVO the delay may be 7ms.

The program supplied with the HFR400 equipment, SATFLAP (SAmple Tube FLow Analysis Program) solves the governing flow equations for the steady flow of gas through a capillary. Unfortunately, the flow through a TSL-H when sampling in-cylinder is not steady and although numerical methods of de-convoluting in-cylinder signals are being researched, they are not yet commercially available (see SAE paper 950160).

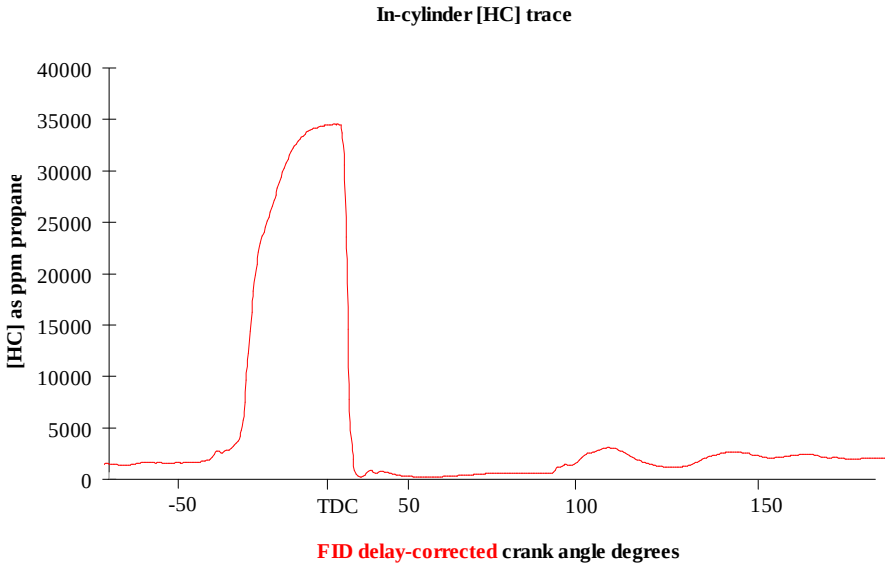


Figure C.15 - Varying signal delay during the cycle causes time axis distortion

Figure C.15 shows a typical in-cylinder signal from an SSP with the x-axis annotated with the crank angle of sample entry into the TSL.

A recognisable feature on firing in-cylinder traces is flame arrival where a sharp reduction in [HC] can easily be discerned. This occurs at high cylinder pressures and the transit delay is generally short (around 1 or 2ms). If an accurate real-time measure of flame arrival time is required, it may be possible to place a flame ionisation wire close to the tip of the sampling capillary. The delay of the Fast FID signal can then be determined from the difference in the signal timing from the two instruments.

Currently, Cambustion do not offer software to produce data corrected for variable engine crank angle delay (this may be available in the future - please contact Cambustion for information). However, SAE papers 940382, 932642, 932643, 922170, 900485, 890579 discuss various research experiments involving in-cylinder sampling.

C.11.8 The Effect of Residual Gas

When examining in-cylinder pre-flame concentrations, it is important to appreciate that they are not 'air/fuel ratio measurements'. The inlet air and fuel are mixed with residuals from the previous cycle, which can be a significant proportion of the unburned pre-spark mixture - particularly at low engine loads.

This effect causes the pre-flame mixture to be significantly leaner than the mixture calculated from the fuel and air flows alone.

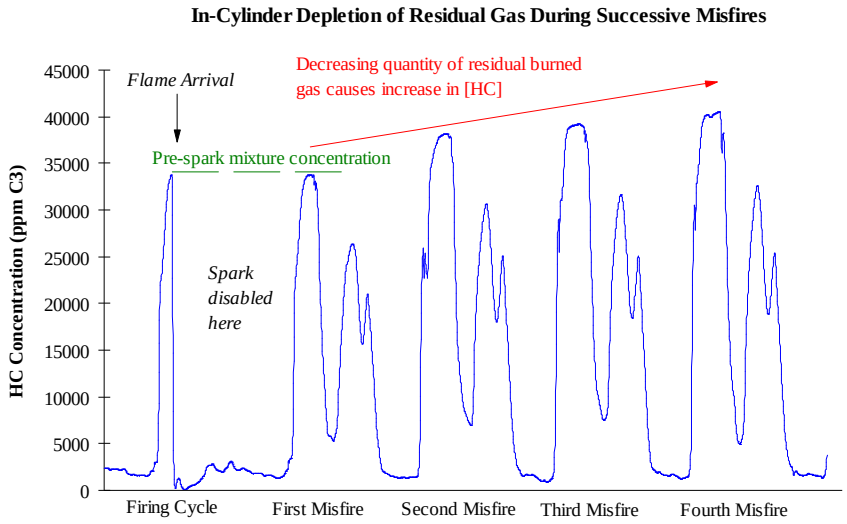


Figure C.16 - Evaluation of residual gas content using successive misfire method

If the engine is misfired, the increase in the peak [HC] level during subsequent cycles can be used to estimate the residual gas fraction. After many misfiring cycles, the pre-spark [HC] should approach the inlet fuel flow divided by the inlet airflow. The residual gas fraction may be estimated from the ratio of the first pre-spark [HC] peak height and the stable level of the [HC] peak height reached after many cycles.

This effect may be seen in Figure C.16. A full discussion of in-cylinder measurement of residual gas concentration is given in SAE paper 900485.

C.11.9 Choking of the Tee-Top Exit

Figure C.17 shows an in-cylinder signal, which is typical of the choking of flow in the tee-top. The signal rises as normal (see Figure C.11) but at the choking sample pressure, the rise in pressure at the FID tube inlet causes a significant increase in the sample flow, which leads to a rise in the signal level as shown. Of course at very low concentrations (burnt gas levels), this effect is difficult to observe, however, in most sampling situations, tee-top choking will lead to signals such as that shown.

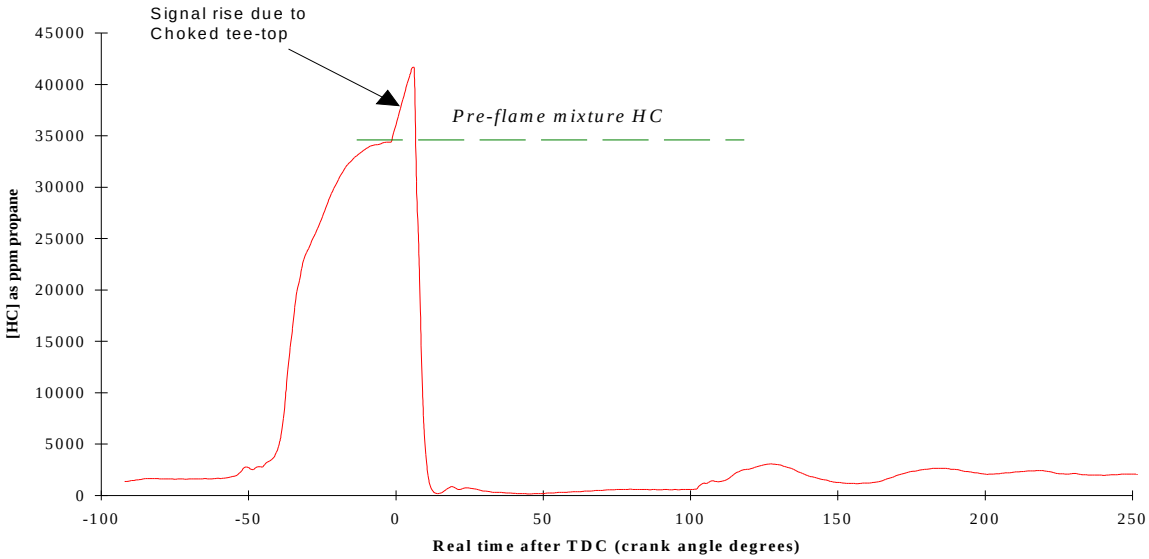


Figure C.17 - In cylinder [HC] with tee-top choked.

C.12 Establishing Range of Linearity

C.12.1 Linearity of In-Cylinder Measurements

In-cylinder HC concentrations may be generally much higher than typical exhaust concentrations. An experiment with a rich span gas and a gas divider can establish the response of the FID with the sampling configuration selected over the range of concentrations of interest.

A high concentration span gas is successively diluted with air. The stoichiometric concentration of propane in air is around 42,000 ppm (4.2%). 5% propane in nitrogen is a reasonable span gas for this experiment (balance air mixtures are not generally available at such high concentrations because of the risk of explosion). It should be noted that the fact that the span gas is balance nitrogen instead of air can lead to some synergistic effects - particularly at concentrations near to the pure span mixture.

C.12.1.1 Setting Fuel and Air Flows

When conducting a linearity check such as the one described above, the fuel and air settings for the flame are important. To achieve the best linearity over the full range, it is best to optimise the FID response (using the technique described in the HFR400 main user guide) with a span gas around half of the maximum concentration to be sampled.

C.12.1.2 Effect of FID Fuel Type

The fuel type used for the FID flame (either pure H_2 or 40%/60% H_2/He) has a significant effect on the high concentration limit of linearity. This is thought to be due to the different flame geometries between the two. The standard fuel recommended with the HFR400 system is pure H_2, if other fuel types are used, then it is very important that the linearity be established by the user.

Tests conducted at Cambustion indicate that with a H_2/He fuelled system, the maximum concentration at which the system is still linear is significantly reduced compared to the pure H_2 fuelled system.

C.12.2 Linearity with CP Chamber Operated at Atmospheric Pressure

Sampling from an environment of atmospheric pressure rather than from the regulated vacuum of the CP chamber has the effect of increasing the density of the sample gas entering the FID tube. This leads to an increased sample mass flow (the sample flow is increased by the ratio of the absolute pressures). This factor, associated with the generally higher HC concentrations encountered in the engine cylinder, means that with the ΔP settings typical of exhaust applications, the instrument can have a non-linear response over the range of concentrations of interest.

The standard sampling system dimensions have been optimised to cope with sample at the inlet of the FID tube at around 0.5bar absolute pressure. When operated with the tee-top at atmospheric pressure, the sample flow is doubled for the same ΔP. Also the flame shape in the FID chamber may be significantly affected by the greatly reduced depression (FID chamber depression is the sum of CP chamber depression and ΔP). This effect may be exacerbated by the use of non-standard fuel gas.

C.12.3 Linearity with CP Chamber Operated Below Atmospheric Pressure

In general, the linearity of FIDs deteriorates as the HC concentration increases to high levels. With the HFR400 system, this effect can be alleviated by reducing the sample flow though the burner flame. The easiest ways to do this for this configuration are to reduce ΔP and/or increase the setting of CP chamber vacuum (which acts to reduce the sample flow density).

C.13 Pressure Independence Issues

This Appendix discusses the issues and techniques for establishing signal independence from sample pressure fluctuations. The two CP configurations are discussed in turn.

C.13.1 Without CP Chamber Fitted

A method of evaluating the sample pressure independence on the signal is by supplying varying pressures of span gas to the tip of the TSL-H and noting the FID signal output.

The experiment shown in Figure C.18 illustrates pressure regulated span gas applied to the tip of the SSP's TSL-H using compression fittings. While noting the signal output, the supply pressure was steadily increased from 0 to 10 bar (the limit of the gas regulator).

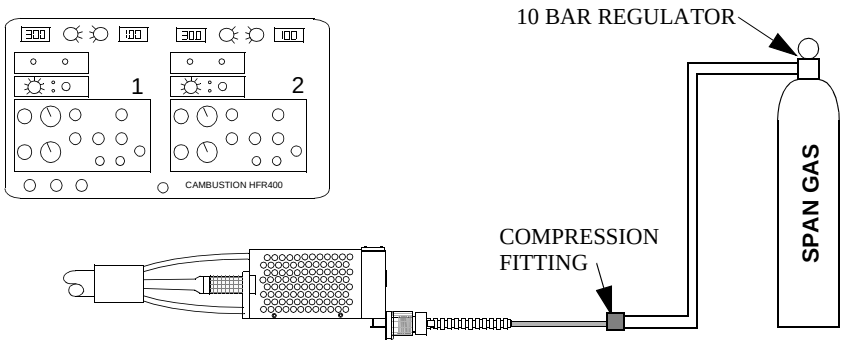


Figure C.18 Simple experiment to investigate sample pressure effect on signal output

It should be noted that this experiment is only suitable for the configuration where the CP chamber is open to atmospheric pressure. With a CP chamber fitted and regulated to a sub-atmospheric CP vacuum, a constant flow of high pressure gas would upset the CP pressure control (as the vacuum system is not designed to regulate under conditions of sustained high sample flow rate). When sampling from the engine, periods of high pressure flow are relatively short and the volume of the CP chamber can be chosen to accommodate them.

The results of the experiment above are shown in Figure C.19.

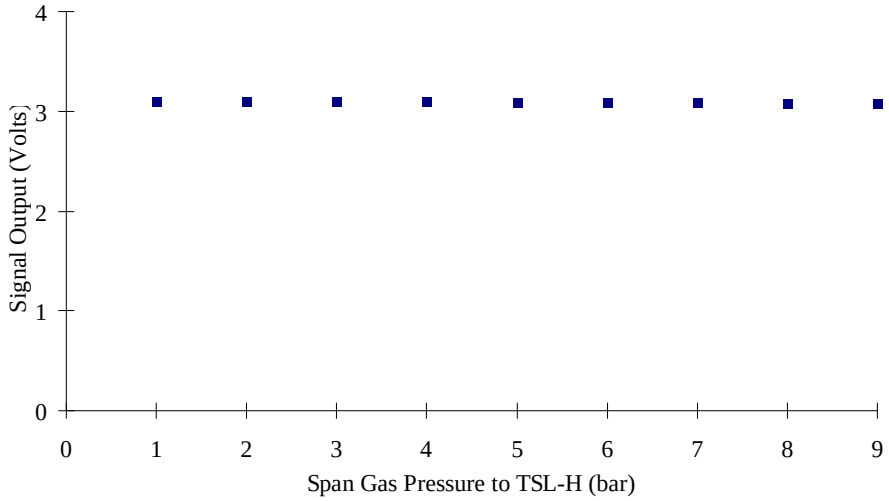


Figure C.19 Signal vs. sample pressure (steady state test)

These results indicate a deviation over the sample pressures tested of about 0.6%. When interpreting results from experiments such as these, it is worth noting that the sustained rapid expansion cooling at the TSL exit into the tee-top will cause an increase in density at this location. If the sample temperature does not recover along the tee-top, this may lead to an increase in the sample mass flow into the FID (remember that only ΔP is fixed).

This effect can lead to a slight signal increase at high applied sample gas pressures. The short duration of this process in the engine sampling situation means that the tee-top is not significantly cooled and this is not a problem during engine experiments.

C.13.1.1 Heated Line Considerations

If using an experiment such as the one above to establish the cylinder pressure limits of linearity (using a high secondary pressure regulator (e.g. 0-100bar)), it is important to heat the TSL to the temperature of the experiment. This is because the choking of flow at exit of the tee top depends upon the density of the sample gas. The LHC may be unable to maintain the line temperature at a sustained high flow rate (the fluctuating flow rate associated with a running engine causes much less heat input to the sample gas). In this case, a high pressure solenoid to limit the exposure time of the high gas flow rate will be required.

NB When working with high pressure gases, always ensure that the pipe and fitting specification are not exceeded and observe safety precautions.

C.13.2 With CP Chamber Fitted

The technique for establishing the independence of the signal level to pressure fluctuations described in Section C.13.1 is not applicable to a configuration with the CP chamber fitted since the vacuum system is not able to cope with the sustained high flow rates of sample gas.

It is possible to simulate short-term pressure fluctuations, which are more typical of an engine situation, by using a solenoid valve connected directly to the gas bottle. This experiment uses a similar configuration to that shown in Figure C.18, but with the solenoid valve immediately adjacent to the end of the TSL-H. If conducting this experiment it is important to minimise the trapped volume between the TSL and the solenoid valve. The duty cycle of the solenoid valve, together with the bottle regulator setting can then be selected to try to match the engine pressure fluctuations.

The absolute pressure in the CP chamber during in-cylinder operation can be measured using a pressure transducer. This may be done by fitting a pressure transducer directly on to the CP chamber. Note that monitoring the analogue output of the ΔP pressure transducer in the MCU is not sufficiently accurate for this measurement since pressure fluctuations will be heavily attenuated down the significant pipe lengths between the transducer and the CP chamber.

Concerning pressure independence, there are two important considerations:

1. The absolute pressure level in the CP chamber itself must not fluctuate significantly (since this will cause a fluctuation in ΔP).

2. The flow in the tee top must be subsonic (i.e. not choked) or there may be a significant pressure drop across a shock wave formed at the tee-top exit.

These two factors must be considered separately.

C.13.2.1 Increasing the CP Chamber Volume

Depending upon the exact sampling configuration and engine conditions being tested, the pressure fluctuations caused by the high TSL-H flows around peak pressure can lead to serious CP vacuum fluctuations with the standard CP configuration (1/8” BSP female hole in base simply plugged).

Note that the effective volume of the CP chamber is significantly higher than simply the volume of the stainless chamber itself. This is because the pipe, which conducts the bleed gas into the CP chamber, has itself a significant volume and an internal diameter of 4mm.

The stability of the pressure in the CP chamber can be significantly improved by connecting a sealed volume directly onto the base of the existing CP chamber. Such a system is shown in Figure C.20.

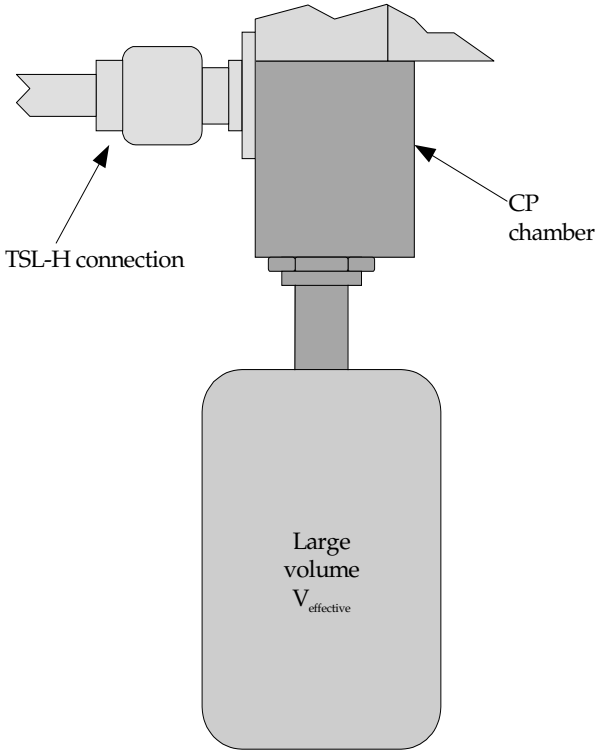


Figure C.20 - CP chamber fitted with additional volume

C.13.2.2 Recommended Configuration for Additional Volume

Engine tests have been conducted on a system at Cambustion (TSL-H 330 mm long, ID 0.016" (0.4mm) heated to 150^{o} C, CP vac 400mmHg, ΔP 30mmHg), with the CP chamber instrumented with a pressure transducer. Results from these tests indicate that pressure fluctuations in the CP chamber can be reduced to about +/- 1mmHg for a worst case engine operating condition (high engine load, low engine speed) using the system shown in Figure C.20 (with sealed volume of 2litres and the pipe joining it to the CP chamber is 300mm long with an ID of 7.5mm).

The length of the pipe joining the volume to the CP chamber base should be kept as small as practically possible since compressibility effects in this joining pipe may be significant.

C.13.2.3 Choking of the Flow in the Tee-Top at High Sample Pressures

The FID signal response corresponding to a situation of choked tee-top exit has a very characteristic appearance (see Figure C.17).

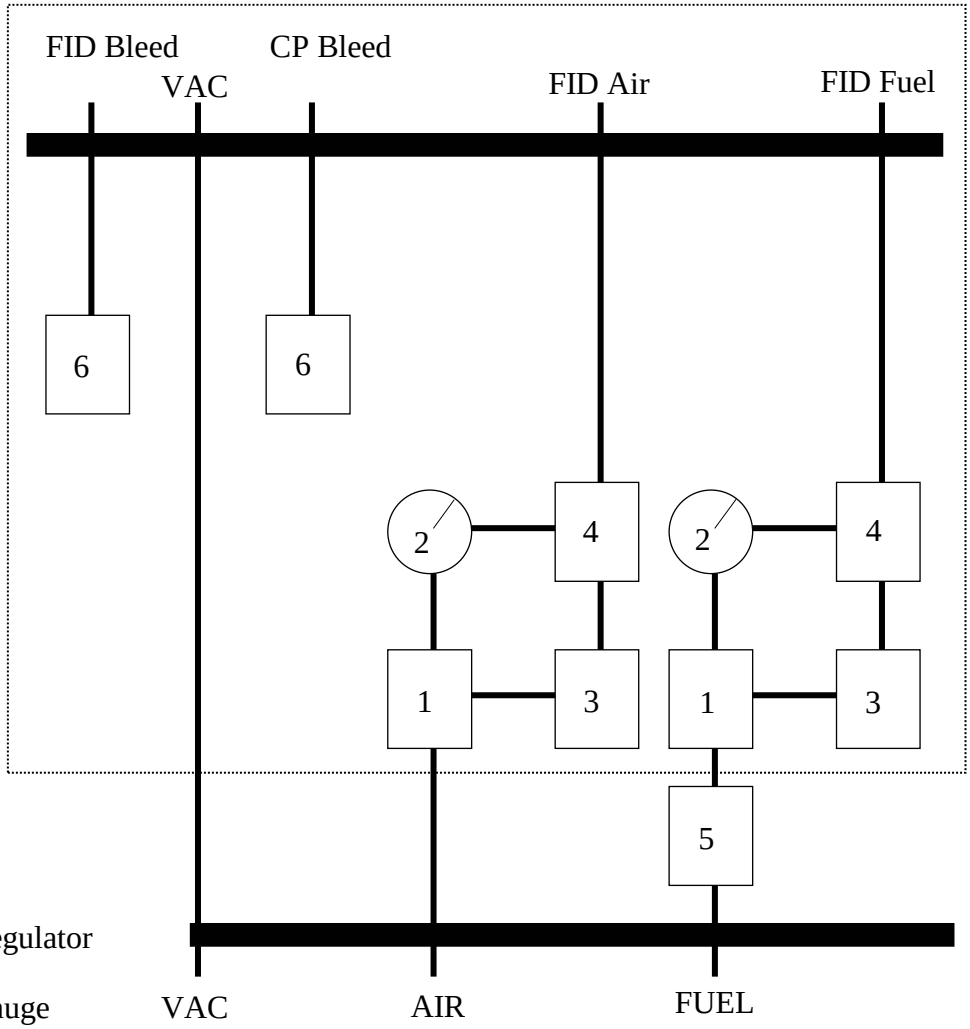
The best way of investigating this phenomenon is to conduct the experiment outlined in Section C.13.2. In practice this may not be possible. The software package SATFLAP can be programmed with the appropriate sampling system dimensions and pressure/temperature conditions. Among the outputs of the program are the velocity of gas in the tee top and the Mach number at tee top exit.

If SATFLAP indicates that this Mach number is approaching 1 (say is greater than 0.8) for the highest sample pressures encountered (maximum cylinder pressure), then further investigation is advised. The envelope of operation for various sampling configurations is outlined in Section C.7.1.2.

D Specification: HFR400

Measurement Principle	Flame Ionisation Detector (FID)
Components Measured	Total Hydrocarbons (THC)
Number of channels	2
Measurement ranges	0-2,000ppmC_3 to 0-1,000,000ppmC_3
Output	0 to 10V, 47Ω. (Output is a true analogue voltage.)
Noise (Peak-Peak)	<±1% of signal
Response time ($T_{90-10\%}$) (CP system)	<4ms (330mm standard sample line length) (response time will be faster for shorter sample line)
Response time ($T_{90-10\%}$) (Atmospheric system)	~1ms (sample flow 20cc/min, sample tube length 50mm)
Zero drift	<±2% of full scale per hour.
Span drift	<±2% of full scale per hour.
Linearity	±2% of full scale (0-50,000ppmC_3)
Fuel gas	Pure hydrogen (H_2/He mix fuel gas option available) at 40 - 50 psi (3bar) gauge.
Air	Zero grade at 75 – 100psi (6bar) gauge.
Calibration Gas	Supply at 75 - 100psi (6bar) gauge
Vacuum	4psi (0.2bar) absolute @ 2 litre/min per channel used – suitable pump available on request.
Sample flow rate (Atmospheric system)	0 - 100cc/min (Varies with sample tube dimensions and FID vacuum)
Sample flow rate (CP system)	~2l/min (Varies slightly with CP and FID vacuum settings)
Ambient temperature	0 - 45°C (Sub zero option available.)
Safety features	Flame out detection and automatic fuel shut off.
Power Supply	AC 50/60Hz, 100-240V.

E Gas Subsystem



1. Pressure Regulator
2. Pressure Gauge
3. Flow Restrictor
4. Solenoid Valve

Duplicated on Channel 2

F Electronics

Board position	Component	Description
IC4	SN74LS05	Hex Inverters O/C
IC5	SN74LS33	Quad 2 I/P Nor Buffers O/C
IC7	SN74LS221	Dual Monostable Multivibrators
C1, C2, C6, C10, C11, C23, C24, C35, C36, C37, C38, C39, C40, C41, C42, C45, C46, C50, C51, C52, C53, C54, C55, C57, C58, C59	47nF	disc ceramic
C3, C4, C5	47nF	polyester capacitor
C7, C25, C26, C28, C29, C30	100nF	polyester capacitor
C8, C9, C31, C32, C33, C34	10µF	6.3V Tantalum
C12	10µF	35V Tantalum
C13	47µF	16V Tantalum
C14	10nF	disc ceramic
C15	2.2µF	250V polyester capacitor
C16, C17, C18, C19, C43, C44	470nF PE	polyester capacitor
C20, C27	470µF	25V electrolytic capacitor
C21, C22, C60, C61	22µF	16V tantalum
C47, C48	10µF	16V tantalum
C56	470µF	10V electrolytic capacitor
DPM1, DPM2, DPM3, DPM4		digital panel meter
D1, D2, D3, D4, D5, D6	IN4001	diode
EC1, EC2, EC11, EC12		4 way MOLEX
EC3, EC15		6 way power connector

EC4, EC5		SMB printed circuit
EC7, EC8		BNC connector
EC9, EC10		3 way MOLEX
EC13, EC14		6 way MOLEX
IC1, IC2	AD595	thermocouple amplifier
IC3	LM339	quad comparator
IC6	SN7407	Hex buffers
IC8	REG 7815	15V regulator
IC9	AD246	clock driver
IC10, IC12	AD204	isolation amplifier
IC11, IC13	TL072	dual opamp
LED1		LED
LED2, LED3		tricolour LED
POT1, POT2, POT3, POT4		1.5W 10 turn pot
PSI	C5180	5 to 180V converter
REL1, REL2		DIL relay
R1, R2	1R5 7W	10%
R3, R4, R5, R6, R7, R8, R31, R32, R33, R34, R35, R36, R42, R43	10K 1/4W	2%
R9, R10, R20, R24, R26, R28, R30, R55, R68, R70, R71	1K 1/4W	2%
R11, R12	5K1 1/4W	2%
R13, R14, R15, R16	200R 1/4W	2%
R17	4K 1/4W	2%
R18	2K 1/4W	2%

R19	11K 1/4W	2%
R21, R22	33K 1/4W	2%
R23, R25, R27, R29	100K 1/4W	2%
R37, R38	300K 1/4W	2%
R39	150R 1/4W	2%
R40, R56, R69	1K 1/4W	2%
R41	510K 1/4W	2%
R44, R57	10K 0.5W	2%
R45, R58	470K 1/4W	0.5%
R46, R59	50M 1/4W	0.5%
R47, R60	20M 1/4W	0.5%
R48, R61, R62	10M 1/4W	0.5%
R49	5M 1/4W	0.5%
R50, R63	2M 1/4W	0.5%
R51, R64	1M 1/4W	0.5%
R52, R65	500K 1/4W	0.5%
R53, R66	200K 1/4W	0.5%
R54, R67	100K 1/4W	0.5%
SW1, SW2		Off-On-(start) double pole SW
SW3, SW4, SW5, SW6		double pole 6-way switch
SW7, SW8		12-way SW only 9 used
TR1, TR2	BC461	PNP transistor
TR3, TR4, TR5, TR6	BFY51	NPN transistor
ZN1, ZN2		bandgap zener
FS1		semi-enclosed fuse

G Ion Generation

The complete mechanisms involved in chemi-ionization are not fully understood; what follows represents current conventional wisdom.

The generation of ions in flames takes place in the reaction zone, and thus the concentration reaches a maximum very shortly after the reaction zone.

The earliest positive ions to appear are CHO^+ and $C_3H_3^+$. Their origin has been attributed to chemi-ionisation as in

$$CH^* + O \rightarrow CHO^+ + e^- \tag{G.1}$$

$$CH + C_2H_2 \rightarrow C_3H_3^+ + e^- \tag{G.2}$$

These reactions produce ion concentrations well above equilibrium levels because combustion is a branched chain reaction that generates molecular fragments (e.g. CH and O) in the reaction zone in anomalously large quantities. The positive ions change identity, particularly by proton transfer, creating a complex ion spectrum.

Recombination is dominated by

$$H_3O^+ + e^- \rightarrow 2H + OH \tag{G.3}$$

Negative ions are present in flames, but their mobility is very low compared with electrons, which dominate the ionisation signal.

The number of ion pairs generated has been established in many experiments to be about 1 ion pair per 10^6 carbon atoms (in aliphatic HC form), taking part in combustion. Using this figure, the maximum FID current can be estimated for a given sample flow. For a hydrocarbon C_mH_n the ion current is given by

$$i = \frac{Q[HC]N_a me}{60\times10^9} \cdot \frac{p}{R_0 T} \text{ (μA)} \tag{G.4}$$

where Q is the sample flow (cc/min), at an absolute pressure p (N/m^2), and absolute temperature T (K), $[HC]$ is the hydrocarbon concentration(ppm), N_a is Avogadro's number (6.023x10^{23}molecules/mol), m is the number of carbon atoms in the HC molecule, e is the electronic charge (1.6x10^{-19}Coulombs), and R_0 is the universal gas constant (8314.4J/mol K).

More detailed information on ion generation may be found in Refs. 1-4.

G.1 References

1. Lawton, J., and Weinberg,F.J., ‘Electrical Aspects of Combustion’, Clarendon Press 1969.

2. Gaydon, A.G., and Wolfhard, H.G., ‘Flames, their Structure, Radiation, and Temperature’, 3rd Ed., Chapman and Hall London 1970.

3. Miller, W.J., ‘Ions in Flames – Evaluation and Prognosis’, 14th Symposium on Combustion, p. 304, 1976.

4. Goodings, J.M., ‘Detailed Ion Chemistry in Methane-Oxygen Flames – Negative Ions’, Combustion and Flame, Vol.36, p.45, 1979.

H Sample Flow Analysis

H.1 Introduction

This Appendix outlines some of the basic relationships, which may be used to predict the sampling system performance.

H.2 Fundamental Sample Flow Governing Equations

The full equations governing the compressible flow of a perfect gas in a constant area duct are:

Continuity
$$\frac{d\rho}{\rho}+\frac{dU}{U}=0 \tag{H.1}$$

Perfect Gas
$$\frac{dp}{p}=\frac{d\rho}{\rho}+\frac{dT}{T} \tag{H.2}$$

Momentum
$$dp+\frac{2\gamma Ma^2\, fpdx}{d}+\rho UdU=0 \tag{H.3}$$

Energy
$$c_p dT+UdU=dQ=c_p dT_0 \tag{H.4}$$

where T_0 is the stagnation temperature and d is the duct diameter.

From the definition of Mach Number
$$\frac{dp}{p}+\frac{dMa}{Ma}=\frac{1}{2}\frac{dT}{T} \tag{H.5}$$

Integrating (H.4)
$$\frac{T_0}{T}=\left(1+\frac{\gamma-1}{2}Ma^2\right)=S \tag{H.6}$$

log diff. (H.6)
$$\frac{dT}{T}=\frac{dT_0}{T_0}-\frac{\left((\gamma-1)Ma\cdot dMa\right)}{S} \tag{H.7}$$

substitution for $\frac{dT}{T}$ from equation H.7 in H.5 gives

$$\frac{dp}{p}=\frac{1}{2}\frac{dT_0}{T_0}-\frac{dMa}{Ma}\left(1+\frac{(\gamma-1)Ma^2}{2S}\right)$$

$$\therefore \frac{dp}{p}=\frac{1}{2}\frac{dT_0}{T_0}-\frac{dMa}{SMa}\left(1+(\gamma-1)Ma^2\right) \tag{H.8}$$

eliminating $\frac{d\rho}{\rho}$ between H.1 and H.2, substituting for $\frac{dT}{T}$ (from H.7) and $\frac{dp}{p}$ (from H.8) in H.2

$$\frac{dU}{U} = \frac{1}{2}\frac{dT_0}{T_0} + \frac{dMa}{SMa} \tag{H.9}$$

divide H.3 by p

$$\frac{dp}{p} + 2\gamma Ma^2 f\frac{dx}{d} + \gamma Ma^2\frac{dU}{U} = 0 \tag{H.10}$$

substitute for $\frac{dp}{p}$ (from H.10) and $\frac{dU}{U}$ (from H.9)

$$\frac{dMa}{Ma} = \frac{(1+\gamma Ma^2)SdT_0}{2(1-Ma^2)T_0} + \frac{2f\gamma Ma^2 Sdx}{(1-Ma^2)d} \tag{H.11}$$

$$dQ = hd\pi dx(T_w - T) = c_p dT_0 \tag{H.12}$$

Where h is the film heat transfer coefficient and T_w is the wall temperature.

The actual analysis contained in the software packages assumes isothermal flow, but the above equations are included for completeness since they form the starting point for a fuller analysis.

Exact solution of the above equations reveals that the capillary flow is very nearly isothermal, apart from a short region at inlet and close to the exit if it is choked (or almost choked).

H.3 Simplified flow analysis - isothermal flow

For isothermal, constant area, one-dimensional flow of a perfect gas, mass flow $\dot{m}$, in a tube of area A, and length L is:

$$\left(\frac{\dot{m}}{A}\right)^2 = \frac{p_1^2 - p_2^2}{2RT\left(2f\frac{L}{d} + \ln\frac{p_1}{p_2}\right)} \tag{H.13}$$

The log term can normally be neglected, and then for laminar flow ($f = \frac{16}{\mathrm{Re}}$)

$$\dot{m} = \frac{(p_1^2 - p_2^2)\pi d^4}{256\mu RTL} \tag{H.14}$$

and for small Δp

$$\dot{m} = \frac{\Delta p \pi d^4 \rho}{128 \mu L} \tag{H.15}$$

Here p_1 and p_2 are the inlet pressures, R the gas constant, T the temperature and f the friction factor. Note that in isothermal flow of perfect gases, the Reynolds number is a constant, and therefore so is f.

A useful relationship for the velocity at any point, x, along the tube can be found from equation H.13 as

$$\frac{1}{U} = \sqrt{\frac{4fL}{RTd}\left(\frac{p_1^2}{p_1^2 - p_2^2} - \frac{x}{L}\right)} \tag{H.16}$$

For turbulent flow of moderate Reynolds Number, 3000>Re>50000, assuming smooth pipes, f is given approximately by

$$f = 0.079(\mathrm{Re})^{-1/4} \tag{H.17}$$

The flow between these Reynolds numbers is transitional, and of indeterminant f. A value of 0.0085 will not be in error by more than about 30%. In the SATFLAP software the assumption is made:

$$f = \frac{16}{\mathrm{Re}} \qquad \mathrm{Re} \le 2500$$

$$f = 0.0064 \qquad \mathrm{Re} > 2500$$

Although the expression H.13 is for compressible flow, it does not recognise the phenomena of choking and if the exit Mach number, Ma_2, implicit in H.13 is greater than $\frac{1}{\gamma}$, where γ is the ratio of specific heats, then the flow will be choked, i.e., $Ma_2 = \frac{1}{\gamma}$ and the mass flow must reduce.

In reality, the isothermal idealisation breaks down at a choked exit, since it requires infinite heat transfer. While the actual exit Mach number will be nearer to unity, $\sqrt{\gamma RT_{tube}}$ will over-estimate the exit flow velocity since the exit gas temperature will have fallen below T_{tube}. Fortunately, differences in the mass flow arising from the assumptions of adiabatic or isothermal are only of the order of 20%, and therefore isothermal behaviour is assumed throughout.

It will be observed from the equations above that the mass flow, and hence the FID response is a function of the pressure drop across the sample tube (whether or not it is choked). In many applications, the sample source pressure varies significantly, and measures must be taken to avoid this affecting the results. CP sampling systems are required in this case.

H.4 Transit Time

Equation H.16 may also be used to find the transit time for a particle moving with the mean axial velocity. It will be seen below (Section H.5) that although there are steep radial velocity gradients in the sample tubes, the transit time obtained in this way is the appropriate one. Neglecting the $\ln\frac{p_1}{p_2}$ term, the transit time, T_τ, is given by

$$T_\tau = \sqrt{\frac{16\,fL^3}{9RTd}\frac{\left[p_1^3 - p_2^3\right]^2}{\left[p_1^2 - p_2^2\right]^3}} \qquad \text{(H.18)}$$

H.5 Time Constant

The papers by Taylor (ref H.8.2, H.8.3) give all the information that is required to estimate the time constant for both laminar and turbulent incompressible flows. Reproduced below are some essentials of the analysis given in these papers.

H.6 Diffusion of Concentration Fluctuations - Laminar Flow

The diffusion equation in cylindrical co-ordinates is

$$D\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial x^2}\right) = \frac{\partial C}{\partial t} + U_0\left(1 - \frac{4r^2}{d^2}\right)\frac{\partial C}{\partial x} \qquad \text{(H.19)}$$

(D = molecular diffusion coefficient, C = concentration, r = radius, d = tube diameter, x = axial distance, t = time.)

If axial variations in C are considered to be small (which will be justified below), then the solution of (H.19) is

$$C = e^{-\alpha t} J_0(r\alpha^{1/2} D^{-1/2}) \qquad \text{(H.20)}$$

where J_0 is the order zero Bessel function.

The boundary condition $\frac{\partial C}{\partial r} = 0$ at $r = d/2$ ensures that

$$J_1\left(\frac{d}{2}\alpha^{1/2} D^{-1/2}\right) = 0 \qquad \text{(H.21)}$$

α is thus found, and substitution into equation H.20 reveals that the time for a radial concentration gradient to decay to $\frac{1}{e}$ of its initial value is given by

$$t = \frac{d^2}{57.8D} \qquad \text{(H.22)}$$

If the concentration gradient is spread over a length of the order L_c, and the centreline velocity is $U_0 = 2U$, then if cross stream diffusion is to be dominant

$$\frac{L_c}{U_0} >> \frac{d^2}{57.8D} \tag{H.23}$$

This assumption is generally well met (as will be seen below) and it can easily be shown that dispersion of the mean axial concentration gradient about a plane moving with the mean velocity is determined by the solution of

$$k\frac{\partial^2 C_m}{\partial x_1^2} = \frac{\partial C_m}{\partial t} \tag{H.24}$$

where $x_1 = x - Ut$, k is an effective diffusion coefficient, given by

$$k = \frac{d^2U^2}{192D} \tag{H.25}$$

and x_1 is a plane moving at the mean velocity.

It is seen here that a large value of D is advantageous for maintenance of sharp concentration gradients in the presence of dispersion by axial velocity gradients.

The solution of equation H.24 for the case of a step change of concentration at $t = 0$, $x = 0$ is

$$\frac{C}{C_0} = \frac{1}{2} \pm \frac{1}{2} erf\left(\frac{x_1}{2\sqrt{kt}}\right) \tag{H.26}$$

Tables for erf show that the length over which the concentration changes from $0.9C_0$ to $0.1C_0$ is given by

$$L_c = 3.62\sqrt{kt} \tag{H.27}$$

A time constant T_c, may be defined as

$$T_c = \frac{L_c}{U} \tag{H.28}$$

We are now in a position to check the validity of equation H.23. If we restrict ourselves to considering the behaviour at the end of the tube i.e. where $x = L$, $t = \frac{L}{U}$ then H.23 is equivalent to requiring

$$\frac{LD}{Ud^2} >> 0.02 \tag{H.29}$$

where L is the tube length reached after time t. For in-cylinder sampling, typical values for sample lines are $d \approx 0.33mm$, $U \approx 50ms^{-1}$, $D \approx 20mm^2s^{-1}$, $L \approx 350mm$ and E.29 is well satisfied.

For exhaust sampling, $d \approx 0.66mm$, $U \approx 10ms^{-1}$, $D \approx 20mm^2s^{-1}$, $L \approx 350mm$ and E.29 is again well satisfied. For the FID tube itself, the condition is again well met.

From H.28 and H.29, T_c (at $x = L$), may be written

$$T_c = 3.62\sqrt{\frac{kL}{U^3}} \tag{H.30}$$

where k is an effective coefficient of diffusion.

It is convenient to express T_c in terms of the applied pressure, rather than U. Then we find, for small Δp, i.e. incompressible flow,

$$T_c = 1.48\sqrt{\frac{\mu L}{D\Delta p}} \tag{H.31}$$

Now for self-diffusion in simple gases $\frac{\mu}{D\rho}$ lies in the range 0.6 to 0.8 (i.e. $\nu \approx D$), and here we take the ratio as 0.7

Finally, then, we have for incompressible, isothermal, laminar flow:

$$T_c \approx 1.24L\sqrt{\frac{p}{\Delta pRT}} \tag{H.32}$$

which has the advantage of simplicity, and is sufficiently accurate for prediction purposes. Note that T_c is **not** a function of tube diameter.

For compressible, isothermal, laminar flow, it has been shown that (ref. H.8.4)

$$T_c \approx 1.24L\sqrt{\frac{(p_1^2 + p_2^2)}{RT(p_1^2 - p_2^2)}} \tag{H.33}$$

Once again T_c is independent of d.

H.7 Diffusion of concentration fluctuations - turbulent flow

The turbulent flow situation was approached by Taylor (H.8.2) by using the fact that there is a universal velocity profile in fully developed turbulent pipe flow. In such a case, the 'universal' velocity profile is given by

$$\frac{U_0 - U}{\nu_*} = f(z) \tag{H.34}$$

where $$z = \frac{2r}{d}\ ,\ \nu_* = \sqrt{\frac{\tau_w}{\rho}} \tag{H.35}$$

where τ_w is the wall shear stress and ρ the fluid density.

Using Reynolds analogy between mass and momentum transport, Taylor showed that the rate, Q, at which matter is diffused axially with respect to planes moving with the mean flow is given by

$$Q = -1.25\pi d^3 \nu_* \frac{dC_{x_1}}{dx_1} \tag{H.36}$$

where $x_1 = x - Ut$, and C_{x_1} is the mean concentration at x_1. Thus the effective diffusion coefficient, k, is given by

$$k = 5.05 d \nu_* \tag{H.37}$$

ν_* can be obtained from the relationships for the friction factor in turbulent flow since by definition

$$\frac{\nu_*}{U} = \sqrt{\frac{f}{2}}$$

and many expressions exist for f as a function of Re.

For Re<50000 for example, the approximate expression

$$f = 0.079(\mathrm{Re})^{-1/4} \tag{H.38}$$

is often used. In this case k is given by

$$k \approx dU(\mathrm{Re})^{-1/8} \tag{H.39}$$

For turbulent, isothermal, incompressible flow, results from ref. H.8.2 may be used to show that

$$T_c \approx 1.44L(\mathrm{Re})^{-3/16}\sqrt{\frac{p}{\Delta pRT}} \tag{H.40}$$

By analogy with the laminar result, it is inferred that for turbulent, isothermal, compressible flow,

$$T_c \approx 1.44L(\mathrm{Re})^{-3/16}\sqrt{\frac{\left(p_1^2 + p_2^2\right)}{RT\left(p_1^2 - p_2^2\right)}} \qquad \text{(H.41)}$$

The latter two results are for smooth pipes. Overall it would be wise to treat the turbulent results with caution, but the trends should be correctly predicted.

The results given above form the basis for the SATFLAP software packages supplied with the HFR400 system.

H.8 References

1. White, F.M., 'Fluid Mechanics', McGraw Hill, 1979.

2. Taylor, G.I., 'Dispersion of soluble matter in solvent flowing slowly through a small tube.' 1953, Proc.Roy.Soc. A,219,186.

3. Taylor, G.I., 'The dispersion of matter in turbulent flow through a pipe.' 1954a, Proc.Roy.Soc. A, 223,446.

4. Smith, R. 'Loss of frequency response along sampling tubes for measurements of gaseous composition at high temperatures.', J. Fluid Mechanics 1989, vol. 208, pp25-43.

I Software

I.1 Introduction

The software is supplied as .EXE files on 5.25" and 3.5" discs, suitable for operation with IBM PC's and compatible.

Contact Cambustion if you desire any customising of the software, or further information.

The program is based on the equations introduced in Appendix H. The prediction of the time constant should be regarded as a guide, as the flame itself has an effect that has not been analysed, and only an approximate correction for the effect of compressibility on the time constant and entry length effects have been included. One-dimensional airflow has been assumed throughout.

I.2 SATFLAP1 – BST systems

This software is used to predict flow rates, time constants, etc. for the simple single tube sampling system.

A full menu is provided in order to help understand and run the package

I.3 SATFLAP3 – CP systems

This software predicts the same parameters as SATFLAP1, but for the tee piece sampling system.

A full menu is provided in order to help understand and run the package.

The dimensions of a standard tee piece are :

tee-top	L=24mm	d=0.046"
FID tube	L=20mm	d=0.008"

J Final disposal of this product

If you are within the European Union, special conditions apply to the final disposal of this equipment when it reaches the end of its useful life.

Please do not scrap via usual domestic or industrial refuse systems. Contact Cambustion for collection and disposal in accordance with The Waste Electrical and Electronic Equipment (WEEE) Directive (2002/96/EC).

K Useful Addresses

Capillary tubing

Coopers Needle Works Ltd, 261/265 Aston Lane, Birmingham, West Midlands, UK.
B20 3HS.
Tel. +44 121 356 4719

Diamond/shellac cutting wheels

Agate and General Stonecutters, 25 Hatton Gardens, London. EC1N 8BA.

Test Gases

BOC, Dunhams Lane, Letchworth, Herts., UK. SG6 3DB.
Tel. +44 1462 77222

(UK and non EEC)

Air Products Ltd., Special Gases Group, Weston Road, Crewe, Cheshire, UK. CW1 1BT
Tel: +44 1345 1778800 Fax: +44 1270 250742

(European Union)

Air Products S.A., Special Gases Group, Zoning Industriel de Keumiee, B-5140, Sombrette, Belgium.
Tel: +32 71 82 21 11

(USA)

Air Products and Chemical Inc., Speciality Gas Department, 7201 Hamilton Boulevard, Allentown, PA 181195-1501, USA.
Tel: +1 800 272 4427

Air Products, Station Road. Barnham. Thetford, Norfolk, UK. IP24 2PT.
Tel. +44 1842 89364

General Flow Fittings

Valeader Pneumatics, Unit 19 Coral Park Estate. Henley Road. Cambridge, UK. CB1 3DY.
Tel. +44 1223 350194

Swagelok Fittings

North London Valve and Fitting Co Ltd., 34 Capitol Way, Capitol Industrial Park, London. NW9 0EQ .

L FID Relative Sensitivities

The following tables have been reproduced from 'Response Factors for Gas Chromatographic Analysers' a paper by W.A. Dietz of Esso Research and Engineering Co., Linden, New Jersey and details the relative response of FIDs to various hydrocarbon compounds.

Normal Paraffins (1,3)	Relative Sensitivity
Methane	0.97
Ethane	0.97
Propane	0.98
Butane	1.09
	(1.03)(3)
Pentane	1.04
Hexane	1.03
Heptane	1.00
Octane	0.97
Nonane	0.98

Branched Paraffins (1,3)	Relative Sensitivity
Isopentane	1.05
2.2 Dimethylbutane	1.04
2.3 Dimethylbutane	1.03
2 Methylpentane	1.05
3 Methylpentane	1.04
2 Methylhexane	1.02
3 Methylhexane	1.02
2.2 Dimethylpentane	1.02
2.3 Dimethylpentane	0.99
IMT4 Ethylcyclohexane	0.98
IMC4 Ethylcyclohexane	0.96
1.1,2 Trimethylcyclohexane	1.01
Isopropylcyclohexane	0.93
Cycloheptane	1.01

Aromatics (1,3)	Relative Sensitivity
Benzene	1.12
Toluene C7H8	1.07
Ethylbenzene	1.03
para-Xylene	1.00
meta-Xylene	1.04
ortho-Xylene	1.02
1M2-Ethylbenzene	1.02
1M3-Ethylbenzene	1.01
1M4-Ethylbenzene	1.00
1,2,3 Trimethylbenzene	0.98
1,2,4 Trimethylbenzene	0.97
1.3,5 Trimethylbenzene	0.98
Isopropylbenzene	0.97
IM2 Isopropylbenzene	0.99
IM3 Isopropylbenzene	1.01
IM4 Isopropylbenzene	0.99
sec. Butylbenzene	1.00
tert. Butylbenzene	1.02
n-Butylbenzene	0.98

Unsaturates (1)	Relative Sensitivity
Acetylene	1.07
Ethylene	1.02
Hexene-1	0.99
Octene-1	1.03
Decene-1	1.01

Aldehydes (1)	Relative Sensitivity
Butyraldehyde	0.62
Heptanoic aldehyde	0.77
Octaldehyde	0.78
Capric aldehyde	0.80

Alcohols (1,3)	Relative Sensitivity
Methanol	0.23
Ethanol	0.46
n-Propanol	0.60
Isopropanol	0.53
n.Butanol	0.66
Isobutanol	0.68
sec.Butanol	0.63
tert. Butanol	0.74
Methylisobutylcarbinol	0.74
Methylamyl alcohol	0.65
Hexyl alcohol	0.74
Octyl alcohol	0.85
Decyl alcohol	0.84
Pentoxol	0.60

Acids (1)	Relative Sensitivity
Formic	0.01
Acetic	0.24
Propionic	0.40
Butyric	0.48
Hexanoic	0.63
Heptanoic	0.61
Octanic	0.65

Nitrogen Compound	Relative Sensitivity
Acetonitrile	0.39
Trimethylamine	0.46
tert-Butylamine	0.54
Diethylamine	0.61
Aniline	0.75
di-n-butylamine	0.75

Esters (1,3)	Relative Sensitivity
Methlyacetate	0.20
Ethlyacetate	0.38
Isopropylacetate	0.54
n-Butylacetate	0.55
Isoamylacetate	0.62
Methylamylacetate	0.63
Ethyl-(2)-ethylhexanoate	0.72
Hexylcaproate	0.78
Cellosolve acetate	0.50

Ketones (1)	Relative Sensitivity
Acetone	0.49
Methylethylketone	0.61
Methylisobutylketone	0.71
Ethylbutylketone	0.71
Diisobutylketone	0.72
Ethylamylketone	0.80
Cyclohexanone	0.72
Pentoxone	0.56

Others (Solvents)	Relative Sensitivity
Cellosolve	0.45
Butyl Cellosolve	0.62
Isophorone	0.85
Thiophane	0.57

M Gas specification

M.1 Hydrogen

The following specification is recommended for the hydrogen supply.

Grade	Total purity by volume	Maximum level of impurities (ppm)			
		THC	$CO+CO_2$	H_2O	O_2
Hydrogen 5.0	**99.999%**	**<0.5**	**<0.5**	**<2**	**<3**

M.2 Air

The following specification is recommended for the compressed air supply.

Synthetic air (21% O_2 + 79% N_2) ± 1%

Grade	Total purity by volume		Maximum level of impurities (ppm)		
	O_2	N_2	THC	$CO+CO_2$	H_2O
Zero Air	**99.995%**	**99.999%**	**<0.5**	**<1**	**<3**

Regulators

Regulators should be chosen which are suitable gas and for the low flow rates used by the system. The maximum hydrogen flow rate is approx. 70cc/min (STP) per HSM and maximum airflow rate is approx. 700cc/min (STP) per HSM with HSM supply pressures at the maximum.

Both hydrogen and air supplies should use an Air Products R304 regulator (or similar) with a 0-10bar gauge outlet pressure (maximum MCU supply pressure should be 6.5 bar.).

Contact Air Products (address in Appendix K) for advice on the choice of regulator for span gas.

A keyed snap connector (which is identified by its orange band) is provided in the tool kit to connect to the fuel inlet. This has two variants:

Part No. SS-QC4-D-6M0K2 Accepts 6mm outside diameter piping
Part No. SS-QC4-D-400K2 Accepts 1/4" outside diameter piping

The -400K2 is supplied to customers in the US and the -6M0K2 is supplied to customers elsewhere. The part number is marked on the packaging – select the piping used accordingly. A suitable inside diameter would be 4mm. To assemble the fitting, insert the piping so that it meets with the internal shoulder and then tighten one and one quarter turns from finger tight. Connect the other end of the piping to the hydrogen supply.

A different connector is provided in the tool kit for connection of the compressed air. For a compressed air supply, an auto shut off fitting is provided – this can be identified by its red collar – and connects to the air inlet. Again this has two variants

Part No.	SS-QC4-D-6M0	Accepts 6mm outside diameter piping
Part No.	SS-QC4-D-400	Accepts 1/4" outside diameter piping

The -400K2 is supplied to customers in the US and the -6M0K2 is supplied to customers elsewhere. The part number is marked on the packaging. Select the piping used accordingly – nylon or PTFE piping is suitable for this application. A suitable inside diameter would be 4mm. To assemble the fitting insert the piping so that it meets with the internal shoulder and then tighten one and one quarter turns from finger tight. Connect the other end of the piping to the compressed air supply.

Ensure that any compressed gas supplies contain sufficient quantities of gas to last for the whole experiment. As a rough guide, each HSM uses around 30cc/min(STP) H_2 and 300cc/min (STP) air but this will depend on the settings of fuel and air pressures, which should be optimised for each experiment.