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THE NPL STANDARD FLAME: OPERATING INSTRUCTIONS

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ABSTRACT

This report describes the operating instructions for the NPL portable standard flame system based on the Hencken flat flame burner using dry laboratory air and industrial grade (95% nominal purity) propane. It also includes a summary of the temperature field above the burner for equivalence ratios from ϕ = 0.8 to ϕ = 1.4, at an airflow rate of 23 SLPM.

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Leon Rogers, Group Leader, Temperature and Humidity.

CONTENTS

1 TERMINOLOGY

Equivalence ratio (phi):

$$\phi = \frac{(V_{fuel}/V_{air})}{(V_{fuel}/V_{air})_{Stoichiometric}}$$

Where V_{fuel} and V_{air} are the volumetric flow rates for the fuel (in this case, propane) and the air respectively. The subscript *Stoichiometric* identifies the condition of a balanced reaction i.e. no excess oxygen. For $\phi > 1.0$ the flame is rich and for $\phi < 1.0$ the flame is lean.

For propane/air combustion the stoichiometric ratio of fuel/air is approximately 4% by volume at STP.

2 INSTALLATION

Note: The NPL standard flame is designed to be used with dry compressed air and propane gas (of a purity of at least 95%) only. Additionally, it should only be operated with an airflow rate of 23 SLPM and equivalence ratios ranging from ϕ = 0.8 to ϕ = 1.4 Using any other gases or operating a different airflow rate will invalidate the calibration and may damage the burner.

The procedure to ignite the burner can be found in section 3.2.1.

The NPL standard flame system comprises of three components:
1. The burner assembly, including the XYZ linear translation stage and gas delivery tubing.
2. The instrumentation cabinet, comprising of the digital mass flow controllers, flame out detection system, pressure and temperature measurement transducers and the XYZ linear translation stage controller.
3. The Windows 7 PC, running the STD flame control software.

To operate the NPL STD flame, the following additional facilities are needed:
1. Compressed air supply (dry) and regulator, capable of delivering at least 4 bar pressure, with a suitable connection for 6 mm OD tubing.
2. Propane gas supply (nominal purity of 95% or better) and regulator, capable of delivering 4 bar pressure, with a suitable connection for 6 mm OD tubing.
3. Optional for co-flow measurements: Nitrogen gas supply and regulator, capable of delivering 0.5 bar pressure, with a suitable connection for 6 mm OD tubing.
4. Mains power supply (220 V – 240 V) with at least 4 outlets.
5. Exhaust gas extraction hood capable of capturing and removing the burner exhaust gas (see specifications below).
6. Carbon monoxide detector.
7. A flat, stable area to mount the burner assembly and general operating area with a stable temperature of between 15 °C and 25 °C.
8. Water cooling is not required.

Note: To avoid damage, loss of calibration and personal injury, unpacking and installation should be carried out by an experience NPL operator only. The installation instructions follow:
1. Place the burner assembly/XYZ linear translation stage on a flat, level, heat proof surface (an optical table is ideal).
2. Make sure the instrumentation cabinet is placed on the floor, within 1 m of the burner assembly.
3. Provide suitable exhaust gas extraction above the burner – a 0.5 m x 0.5 m hood placed 0.5 m above the burner with 0.5 m.s^{-1} flowrate is ideal.
4. Place the carbon monoxide detector within 0.5 m of the burner.

5. Connect the 'T' shaped tubing quick-connectors (these include PRT's and grey coloured sensor wiring) to the burner inlet air and inlet propane ports. Connect the gas delivery tubes from these connectors to the rear of the instrumentation cabinet.
6. Connect the N_2 co-flow tube from the burner assembly to the instrumentation cabinet (if required) using the supplied quick-connectors.
7. Connect 6 mm tubing (supplied) between the instrumentation cabinet front panel quick connectors and the gas regulators. Each tube is labelled. The propane tube has a non-return valve which must be installed in this line (the green end indicates inlet flow direction).
8. Make sure all connections are gas tight and open the three valves on the front of the instrumentation cabinet.
9. Install the flame out sensor within 0.5 m of the burner such that the port on its front side observes the region immediately above the burner (lining up ca be done later).
10. Connect the two translation stage communication cables from the instrumentation cabinet to the XYZ linear stage beneath the burner.
11. Connect the USB cable labelled "to PC" from the instrumentation cabinet to the Windows 7 PC.
12. Connect the main power distribution board inside the instrumentation cabinet (white way board) to the mains power supply and switch on.
13. Connect the Windows PC and monitor the mains power supply and switch on.
14. Log on to the PC with the following credentials:
    a. Username: GJMS
    b. Password: Quarter416
15. Double click on the desktop icon labelled *NPL STD* flame to start its execution.
16. Once the software has started, follow the operation instructions given in the next section.

Note: for best results, it is important to carefully shield the flame from drafts and excessive air movement. The N_2 co-flow improves the post-flame stability significantly but good shielding is also important with or without N_2 co-flow. Additionally, applying the N_2 co-flow for prolonged periods of time, will cool the burner body significantly and may affect the flame temperature.

3 OPERATION

Once the STD flame software is running (see points 15 and 16 above), you are presented with a window with one of two *Tabs* showing:

1. *Config* – this is where the configuration of the system can be changed.
2. *Operate* – this is where the STD flame is controlled and monitored.

3.1 STD FLAME CONTROL SOFTWARE: *CONFIG TAB*.

The *Config Tab* is shown in Figure 3.1. The settings on this Tab are read only once when the software is started and as such cannot be changed using the STD flame executable. The user will not need to change any of these settings but may need to check if the system is working correctly. If there is need to change any of these settings, NPL can explain how to open the Labview project and make adjustments.

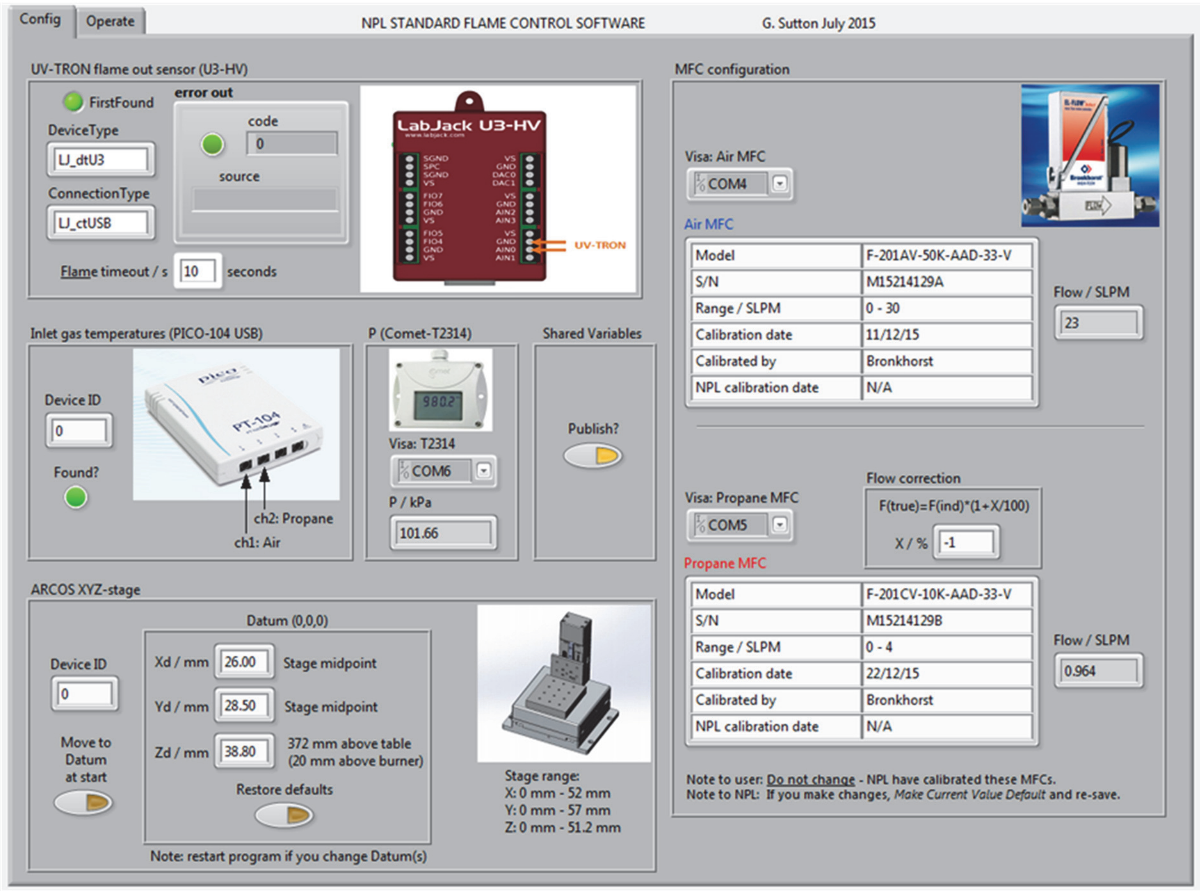
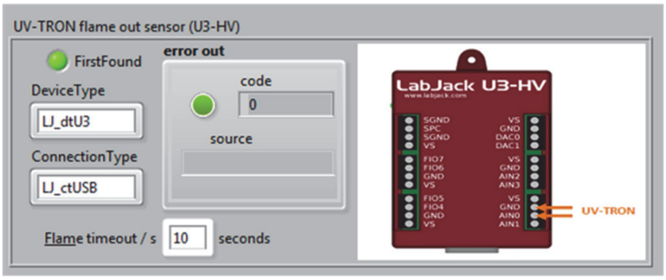


Figure 3.1 the *Config Tab* of the NPL STD flame software.

A description of each component on this Tab follows.

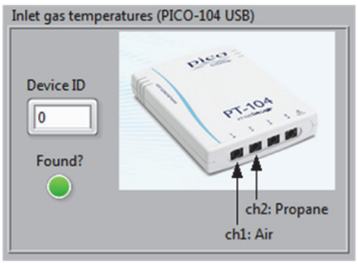
3.1.1 *Config Tab*: UV-TRON flame out sensor (U3-HV)



Description	
Monitors the UV-TRON sensor for a flame out condition.	
Defaults	
DeviceType	LJ_dtU3
ConnectionType	LJ_ctUSB
Flame timeout / s	10
Connections	
-ve	GND
+ve	AIN0

Note: if the *FirstFound* LED is <u>not</u> illuminated, there is a system fault. Quit the software and contact NPL.

3.1.2 *Config Tab*: Inlet gas temperatures (PICO-104 USB)



Description	
Measures the inlet air and propane temperatures.	
Defaults	
DeviceID	0
Connections	
Ch1	Air PRT
Ch2	Propane PRT

Note: if Found? Is not illuminated, there is a system fault. Quit the software and contact NPL.

3.1.3 *Config Tab*: P (Comet- T2314)

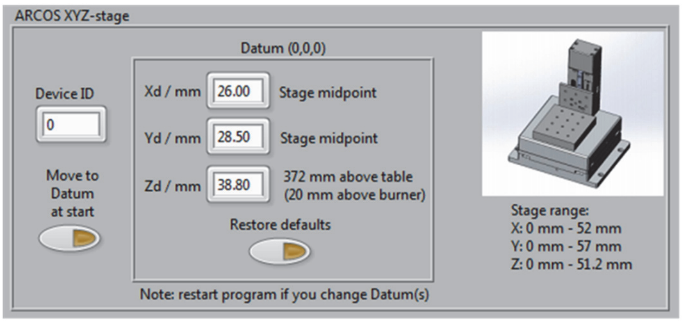
Description	
Measures the atmospheric pressure.	
Defaults	
VISA (RS232)	COM6

Note: if the pressure is not updating in the *P / kPa* indicator, there is a system fault. Quit the software and contact NPL.

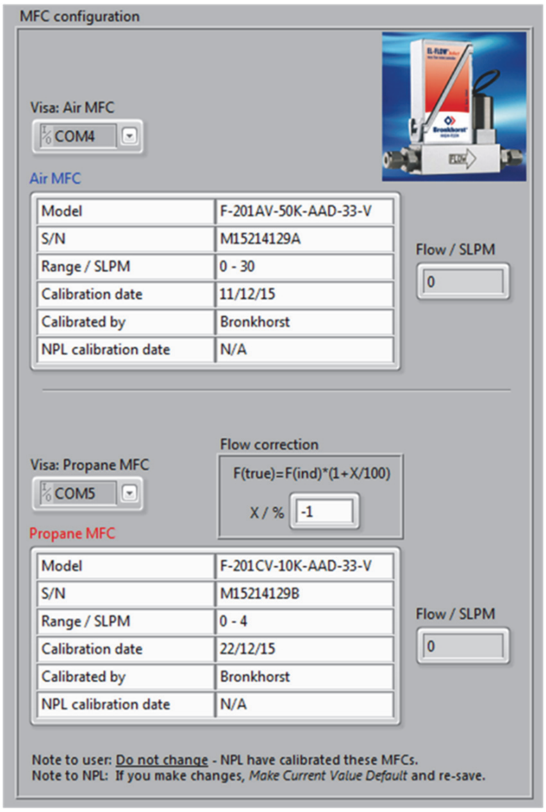
3.1.4 *Config Tab*: Shared Variables

<table>
<tr><td rowspan="4">
</td><td colspan="2">Description</td></tr>
<tr><td colspan="2">Publishes STD flame data including flow, temperature, pressure and XYZ position to the network for use by the Rayleigh scattering software. Deselect when used outside NPL.</td></tr>
<tr><td colspan="2">Defaults</td></tr>
<tr><td>Publish?</td><td>True</td></tr>
<tr><td colspan="3">Note: This option is <u>not</u> selected by default and is for use by NPL to communicate with the separate flame temperature measuring software.</td></tr>
</table>

3.1.5 *Config Tab*: ARCOS XYZ-stage

<table>
<tr><td rowspan="8">
</td><td colspan="2">Description</td></tr>
<tr><td colspan="2">Configures the ARCOS XYZ translation stage that the STD Flame is mounted on. If Move to Datum at start is True, the stage will do so when the program is restarted. Pressing Restore defaults will reset the datum values such that the stage is at its midpoint in the XY plane and 38.8 mm above its lower limit in the Z plane (set for the NPL laser beam delivery height).</td></tr>
<tr><td colspan="2">Defaults</td></tr>
<tr><td>DeviceID</td><td>0</td></tr>
<tr><td>Move to Datum at start</td><td>True</td></tr>
<tr><td>Xd / mm</td><td>26.0</td></tr>
<tr><td>Yd /mm</td><td>28.5</td></tr>
<tr><td>Zd /mm</td><td>38.80</td></tr>
<tr><td colspan="3">Note: by default, the XYZ stage will move to the datum when the software is started. If you wish to de-activate this, contact NPL.</td></tr>
</table>

3.1.6 *Config Tab*: MFC configuration



Description	
Controls the Mass flow controllers (MFC's) and provides for a correction to the propane flow-rate.	
Defaults	
Air MFC	
Visa Air MFC	COM4
Model	F-201AV-50K-AAD-33-V
S/N	M15214129A
Range / SLMP	0 - 30
Calibration date	11/12/15
Calibrated by	Bronkhorst
NPL calibration date	N/A
Propane MFC	
Visa Propane MFC	COM5
Flow correction X / %	-1
Model	F-201CV-10K-AAD-33-V
S/N	M15214129B
Range / SLPM	0 - 4
Calibration date	22/12/15
Calibrated by	Bronkhorst
NPL calibration date	N/A

Note: Do not adjust the *Flow correction* input box. This will invalidate the STD flame temperature calibration. If you believe the flow meters are in error, please contact NPL.

3.2 STD FLAME CONTROL SOFTWARE: *OPERATE TAB*.

The *Operate Tab* is shown in Figure 3.2. Once program execution begins, the flow is <u>not</u> activated but a) the flow, b) the inlet gas temperatures and c) the barometric pressure are continuously monitored and displayed on the RHS of the screen. The System control Tab, labelled d) on the LHS is used to adjust the parameters of flame and is described in greater detail later. Two status LED's are present on the top right of the window (next to the small image of the flame). These indicate if the flame is out (i.e. not ignited) and if fuel is flowing. This is explained in more detail later.

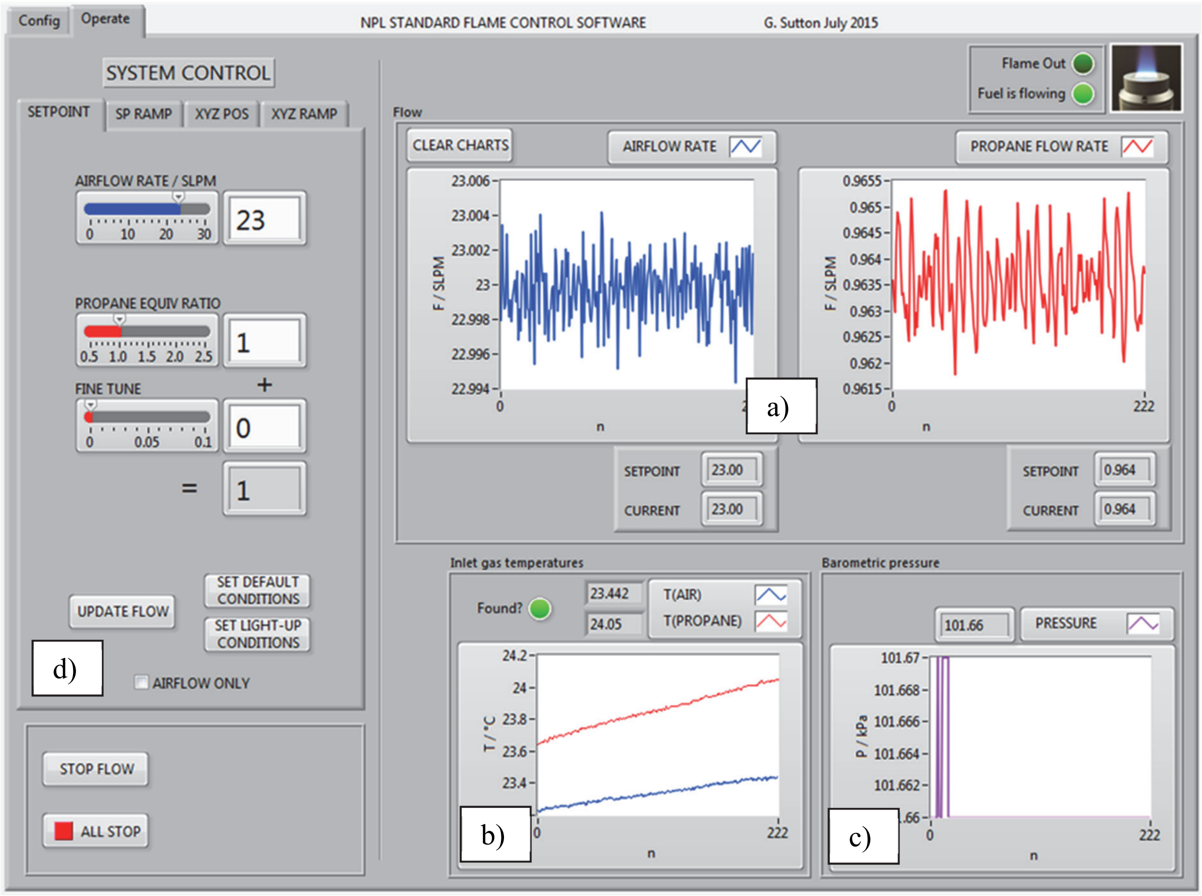
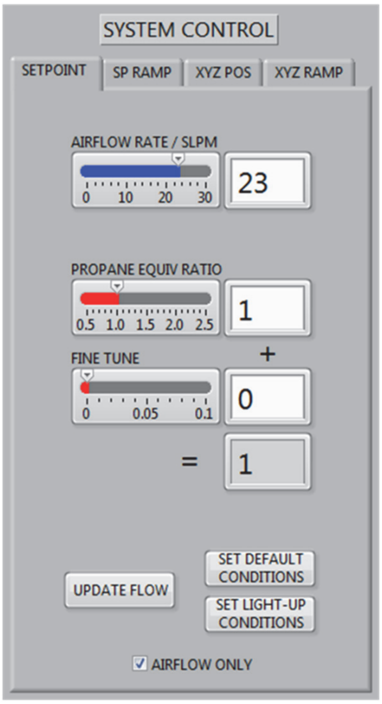


Figure 3.2 the *Operate Tab* of the NPL STD flame software: a) flow indication – blue (air), red (propane), b) inlet gas temperatures, c) barometric pressure and d) Main *system control* Tabs.

3.2.1 Operate Tab: SETPOINT



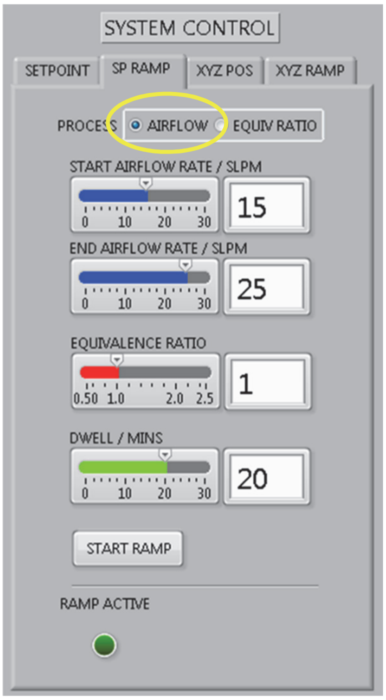
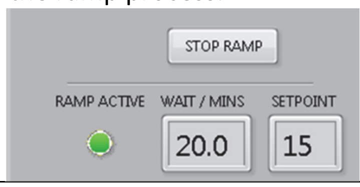
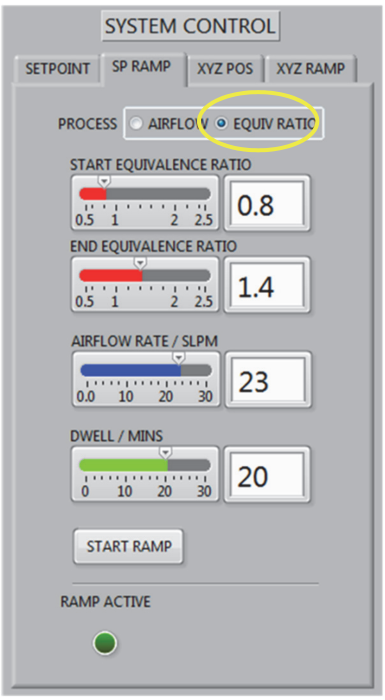
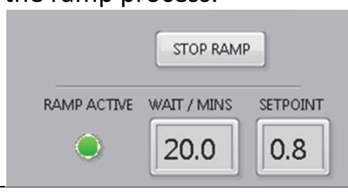
Description: *SETPOINT*
Controls STD Flame with a single air-flow and equiv. ratio set-point.
AIRFLOW RATE / SLPM: Sets the required airflow-rate. Default 23 SLPM, Range: 1 - 30 in 1 SLPM steps. Does not update flow until *UPDATE FLOW* is pressed.
PROPANE EQUIV RATIO: Sets the required propane equivalence ratio (phi). Default 1, Range: 0.5 – 2.5 in 0.1 steps. Does not update flow until *UPDATE FLOW* is pressed.
FINE TUNE: Added to *PROPANE EQUIV RATIO* value as value sent to MFC. Default 0, Range 0.00 – 0.1 in 0.01 steps.
UPDATE FLOW: Sends the new flow-rates to the MFC's to maintain the new airflow and equivalence ratio (the propane MFC calibration correction is also applied).
SET DEFAULT CONDITIONS: Sets the default flow conditions – 23 SLPM airflow, phi = 1.0. The flow is updated immediately.
SET LIGHT-UP CONDITIONS: Sets the flow conditions for lighting the flame - 8 SLPM airflow, phi = 2.5. This produces a small, easily ignitable luminous flame, making it easy to see. The flow is updated immediately.
AIRFLOW ONLY: Checking this box will stop any propane flow and update the airflow – useful for measuring the air temperature above the burner and for quick cooling of the burner after use. Does not update flow until *UPDATE FLOW* is pressed.

Note: the flame is calibrated with an airflow rate of 23 SLPM. Changing this value will invalidate the calibration and for low airflow rates can result in damage to the burner. DO NOT CHANGE.

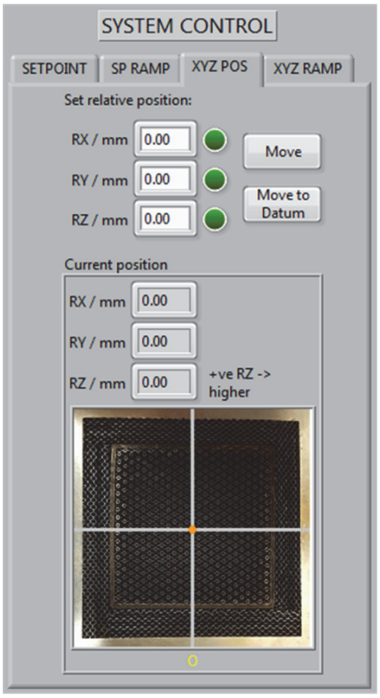
To light the burner:

1. Make sure the air and propane regulators are set open to a pressure of 4 bar.
2. Make sure the shut off values on the front of the instrumentation cabinet are open.
3. Make sure the flame out sensor is adequately positioned to see the region above the burner (i.e. within 0.5 m).
4. *Press the SET LIGHT-UP CONDITIONS* button. An indicator next to the *Flame out* LED will show that the flame is not lit and display a 10 second countdown (there is a small audible beep also).
5. Within 10 seconds, ignite the gas above the burner with a suitable spark ignitor.
6. If the flame does not light within 10 seconds, the propane flow will stop (preventing the escape of significant amounts of propane gas).
7. If the flame ignites but extinguishes after 10 seconds, the flame out sensor is either faulty or not observing the flame. Adjust its position and try again. If you think the sensor is faulty, contact NPL.
8. Once the flame is lit, press the *SET DEFAULT CONDITIONS* button and the airflow rate and propane equivalence ratio will be set to 23 SLPM and 1.0 respectively.
9. The burner takes approximately 90 minutes to reach thermal equilibrium. Measurements should not be made on the STD flame before this time.
10. For airflow only measurements, check the *AIRFLOW ONLY* check box.
11. To extinguish the flame, press the *STOP FLOW* button on the main *Operate Tab*.
12. To exit the program press the *ALL STOP* button on the main *Operate Tab*.

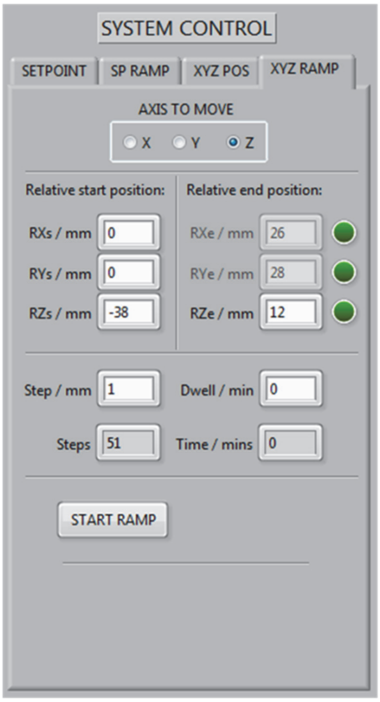
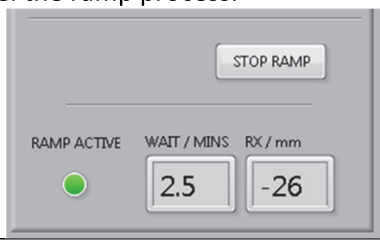
3.2.2 Operate Tab: SP RAMP

<table>
<tr><td rowspan="9">
</td><td>Description: SP RAMP</td></tr>
<tr><td>Perform airflow or equivalence ratio ramps on STD Flame.</td></tr>
<tr><td>PROCESS Checkbox: AIRFLOW selected</td></tr>
<tr><td>Performs an <u>airflow</u> ramp with fixed equivalence ratio</td></tr>
<tr><td>START AIRFLOW RATE / SLPM – the start airflow rate. Default value is 15 SLPM.</td></tr>
<tr><td>END AIRFLOW RATE / SLPM – the end airflow rate. Default value is 25 SLPM.</td></tr>
<tr><td>EQUIVALENCE RATIO – the fixed value of the equivalence ratio. Default value is 1.</td></tr>
<tr><td>DWELL / MINS – the dwell time at each step in the airflow ramp. Default value is 20 mins. Values can range from 1 to 30 mins.</td></tr>
<tr><td>START RAMP – starts the automated ramp in airflow.</td></tr>
<tr><td></td><td>During the ramp process, the RAMP ACTIVE indicator will light, the current set-point will be indicated and the remaining WAIT time at the current set-point will be shown. Pressing STOP RAMP will cancel the ramp process.

</td></tr>
<tr><td rowspan="9">
</td><td>PROCESS Checkbox: EQUIV RATIO selected</td></tr>
<tr><td>Performs an <u>equivalence ratio</u> ramp with fixed airflow rate.</td></tr>
<tr><td>START EQUIVALENCE RATIO – the start equivalence ratio. Default value is 0.8.</td></tr>
<tr><td>END EQUIVALENCE RATIO – the end equivalence ratio. Default value is 1.4.</td></tr>
<tr><td>AIRFLOW RATE / SLPM – the fixed value of the airflow rate. Default value is 23 SLPM.</td></tr>
<tr><td>DWELL / MINS – the dwell time at each step in the airflow ramp. Default value is 20 mins. Values can range from 1 to 30 mins.</td></tr>
<tr><td>START RAMP – starts the automated ramp in equivalence ratio.</td></tr>
<tr><td>During the ramp process, the RAMP ACTIVE indicator will light, the current set-point will be indicated and the remaining WAIT time at the current set-point will be shown. Pressing STOP RAMP will cancel the ramp process.

</td></tr>
<tr><td></td></tr>
<tr><td colspan="2">Note: The NPL calibration is <u>only valid for an airflow rate of 23 SLPM and equivalence ratios between 0.8 and 1.4</u>. Additionally, lowering the airflow rate <u>below</u> 20 SLPM can heat the burner and potentially damage it.</td></tr>
</table>

3.2.3 Operate Tab: XYZ POS

<table>
<tr><td rowspan="8">
</td><th>Description: XYZ POS</th></tr>
<tr><td>Sets the XYZ position of the STD Flame.</td></tr>
<tr><td>RX / mm is the position of the STD Flame relative to Xd (the X stage datum). See Config Tab (Figure 1)</td></tr>
<tr><td>RY / mm is the position of the STD Flame relative to Yd (the Y stage datum).</td></tr>
<tr><td>RZ / mm is the position of the STD Flame relative to Zd (the Z stage datum).</td></tr>
<tr><td>Move – moves the STD Flame to the new relative position RX, RY, RZ. When the MOVE button is pressed and the new position is out of range, the green indicators next to any out of range value will become red. No move will be attempted in a direction with an invalid move position.</td></tr>
<tr><td>Move to Datum – moves the STD Flame to the Datum position (i.e RX = RY = RZ = 0 mm).</td></tr>
<tr><td>Current position: RX / mm, RY / mm, RZ / mm gives the current relative position of the STD Flame. When RZ is positive, the STD Flame position is higher than the datum Zd.
A picture of the burner (viewed from above) with an orange 'spot' is also given. The 'spot' gives an indication of the current XY position and is only a valid when the datum in the XY plane is set to <u>coincide with the centre of the burner</u>.
Note also, the yellow circle at the bottom of the image – this coincides with a yellow sticker fixed to the burner body and can help identify movement direction.</td></tr>
<tr><td colspan="2">Note: the datum position (Xd,Yd,Zd) is set to the <u>midpoint</u> of the x and y stages and 38.8 mm above the lower limit of the z stage. In this configuration, the default measurement position (20 mm above the burner) is <u>exactly 372 mm above the surface that the burner is placed on</u>. If clarification is needed, contact NPL.</td></tr>
</table>

3.2.4 Operate Tab: XYZ RAMP

<table>
<tr><td rowspan="6">
</td><td>Description: XYZ RAMP</td></tr>
<tr><td>Performs a position ramp of the STD Flame in either the X, Y or Z directions.</td></tr>
<tr><td>AXIS TO MOVE – Selects the axis to perform the position ramp on (X, Y or Z).</td></tr>
<tr><td>Relative start position / Relative end position - sets the start / end position of the ramp. Depending on the axis selected, some input boxes will be greyed and cannot be changed. In the example shown, the Z axis has been selected and the start positions for RX, RY and RZ can be set. For RZ, both the start and end positions can be set. If out of range positions are set, the green indicators turn red and the ramp cannot be started.
The default values are:
(RXs, RYs, RZs) = (-26 mm, -28 mm, -38 mm).
(RXe, RYe, RZe) = (26 mm, 28 mm, 12 mm).
These give a good indication of the full range of available movement but should be changed, if for example, you wish to ramp RX across the burner centre, i.e. set RYs to 0 mm.</td></tr>
<tr><td>Step / mm - sets the ramp step size. Default value is 1 mm.
Dwell / mins – the dwell time at each step in the ramp. Default value is 3 mins. Values can range from 0 to 60 mins.
Steps – indicates the number of steps that will be performed.
Time / mins – indicates how long the ramp will take to complete.
START RAMP – starts the position ramp.</td></tr>
<tr><td>During the ramp process, the RAMP ACTIVE indicator will light, the current set-point will be indicated and the remaining WAIT time at the current set-point will be shown. Pressing STOP RAMP will cancel the ramp process.

</td></tr>
<tr><td colspan="2">Note: if you want to get a good idea of how the burner will move during a ramp, set the Dwell time to zero minutes and start the ramp. The burner will perform the ramp quickly and its movement can be observed.</td></tr>
</table>

4 TEMPERATURE FIELD ABOVE THE BURNER

4.1 FLAME TEMPERATURE DURING BURNER WARM-UP

Figure 4.1 shows the measured post-flame temperature 20 mm above the centre of the burner for ϕ = 1.0, 23 SLPM airflow. The temperature of the upper body of the burner was also monitored and is shown on the right-hand scale. The post-flame temperature changes by approximately 1.0 % during the warm-up phase which lasts for approximately 90 minutes.

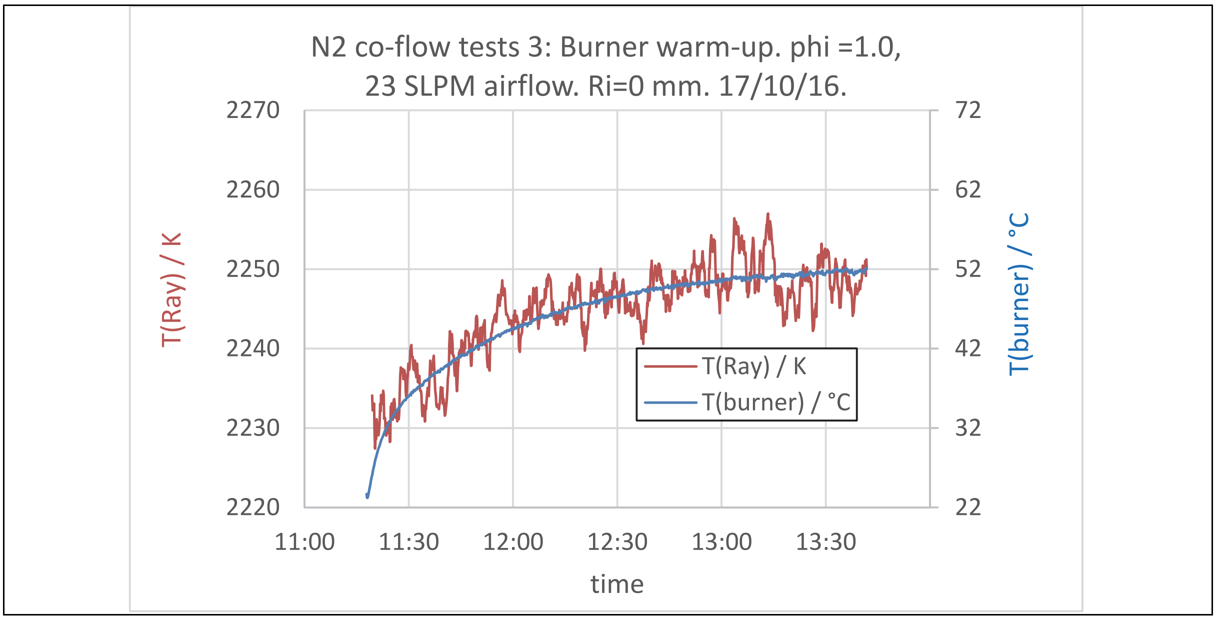


Figure 4.1 Post-flame temperature during burner warm-up, 20 mm above burner centre. The temperature of the upper body of the burner is also shown.

4.2 LONG TERM MEASUREMENTS 20 MM ABOVE BURNER CENTRE

Figure 4.2 shows a) the mean of 10 days measurements of the post-flame temperature 20 mm above the burner centre, b) the variability in temperature over 10 days measurements relative to the mean and c) the inlet temperatures and atmospheric pressure during the tests. There is no obvious correlation between $T_f(\phi)$ and the inlet gas temperatures or atmospheric pressure. See Appendix 1 for tabulated results.

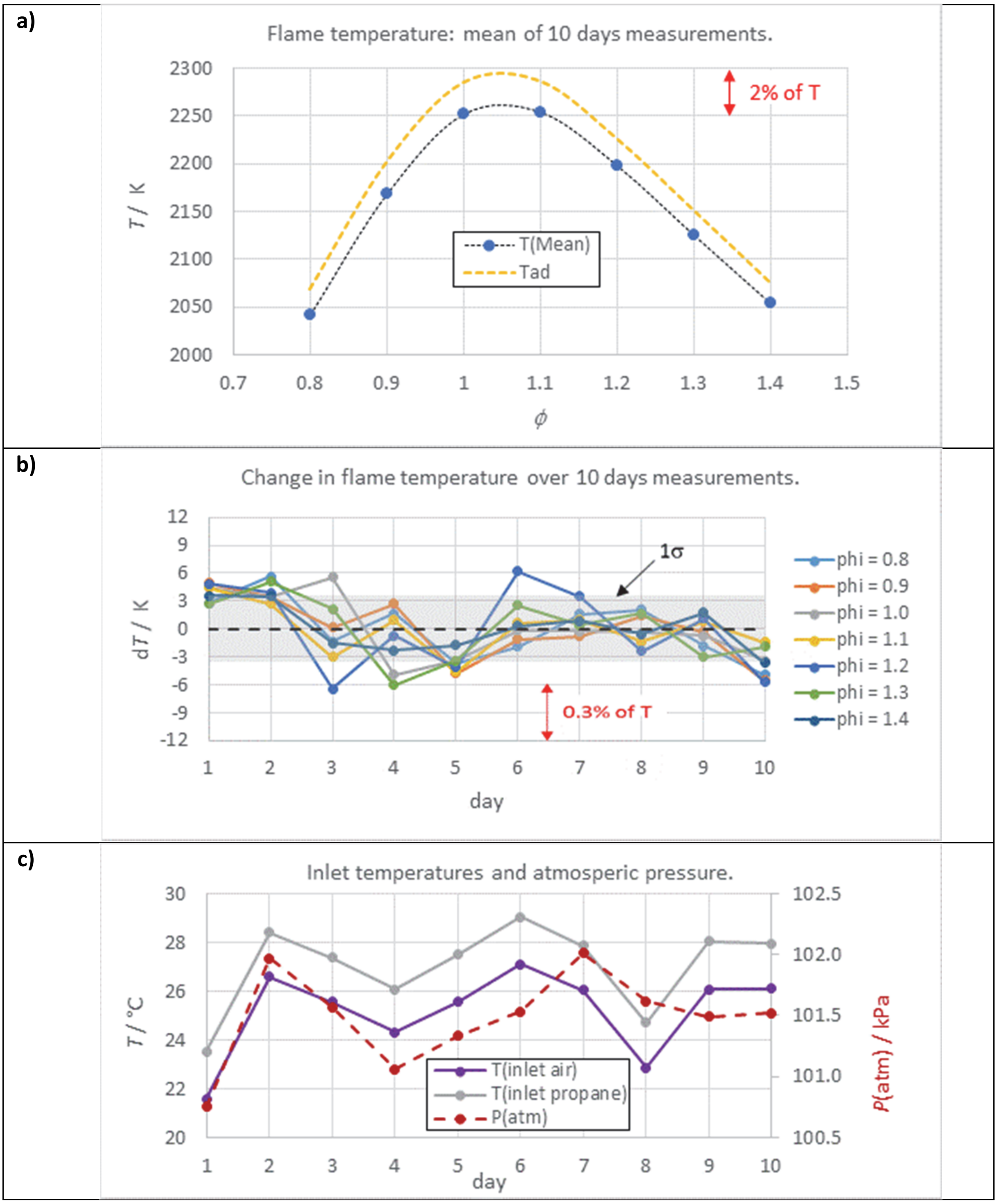


Figure 4.2 Flame temperature 20 mm above the burner centre: a) mean of 10 days measurements, b) variability over 10 days measurements. c) inlet temperatures and atmospheric pressure during the tests.

4.3 TEMPERATURE PROFILES WITH AND WITHOUT N_2 CO-FLOW

The post-flame temperature profile has been measured with and without a nitrogen (N_2) gas co-flow. The co-flow, delivered through a mesh surrounding the central flame/air tubes is highlighted in purple in Figure 4.3. During co-flow measurements, the N_2 output regulator pressure was held at an indicated 0.5 bar and no other flow control was used. Referring to Figure 4.3, horizontal temperature profiles, 20 mm above the burner, were made in a) the x direction and b) the y direction, with and without the N_2 co-flow, for ϕ = 0.8, 1.0 and 1.4. The measurements were repeated on two separate days for heights of 10 mm and 30 mm above the burner.

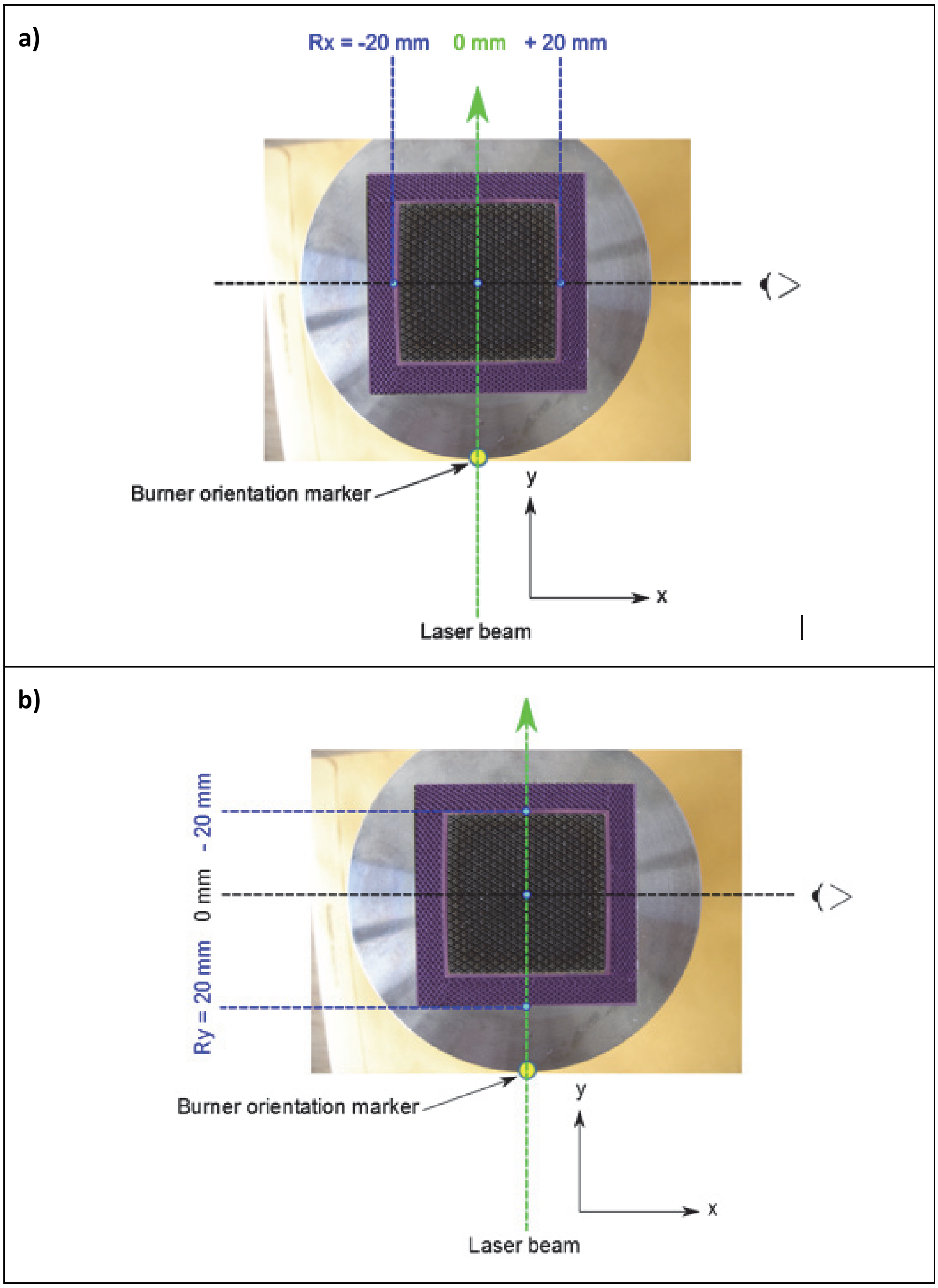


Figure 4.3 Post-flame temperature profile measurement configuration (the burner is viewed from above). The N_2 co-flow delivery region is highlighted in purple. The horizontal temperature profiles were measured a) from R_x = -20 mm to R_x = +20 mm and b) from R_y = -20 mm to R_y = +20 mm. The yellow spot in the figure (also present on the burner itself) indicates the measurement system geometry.

4.3.1 $\phi = 1.0$

Figure 4.4 shows the post-flame temperature profiles a) without co-flow and b) with N_2 co-flow, for $\phi = 1.0$, 23 SLPM airflow. The figure legend has the format $T(R_x, R_y, R_z)$, where R_x, R_y and R_z define the measurement position relative the burner datum, which, in this work is 20 mm above the centre of the burner. i.e. R_z = +0 mm, +10 mm and -10 mm corresponds to heights of 20 mm, 10 mm and 30 mm above the burner respectively and R_x and R_y are as defined in figure 4.3. The R_x profiles are shown as solid markers with dotted lines and the R_y profiles are shown with unfilled markers.

Measurements for R_z = +10 mm (10 mm above the burner) should be used with caution as it has been shown that the species may not have reached chemical equilibrium. Additionally, measurements for $|R_x|$ or $|R_y|$ greater than 15 mm may also be in error due to air mixing and the inherent assumptions used in the Rayleigh thermometry model. See Appendix 1 for tabulated results.

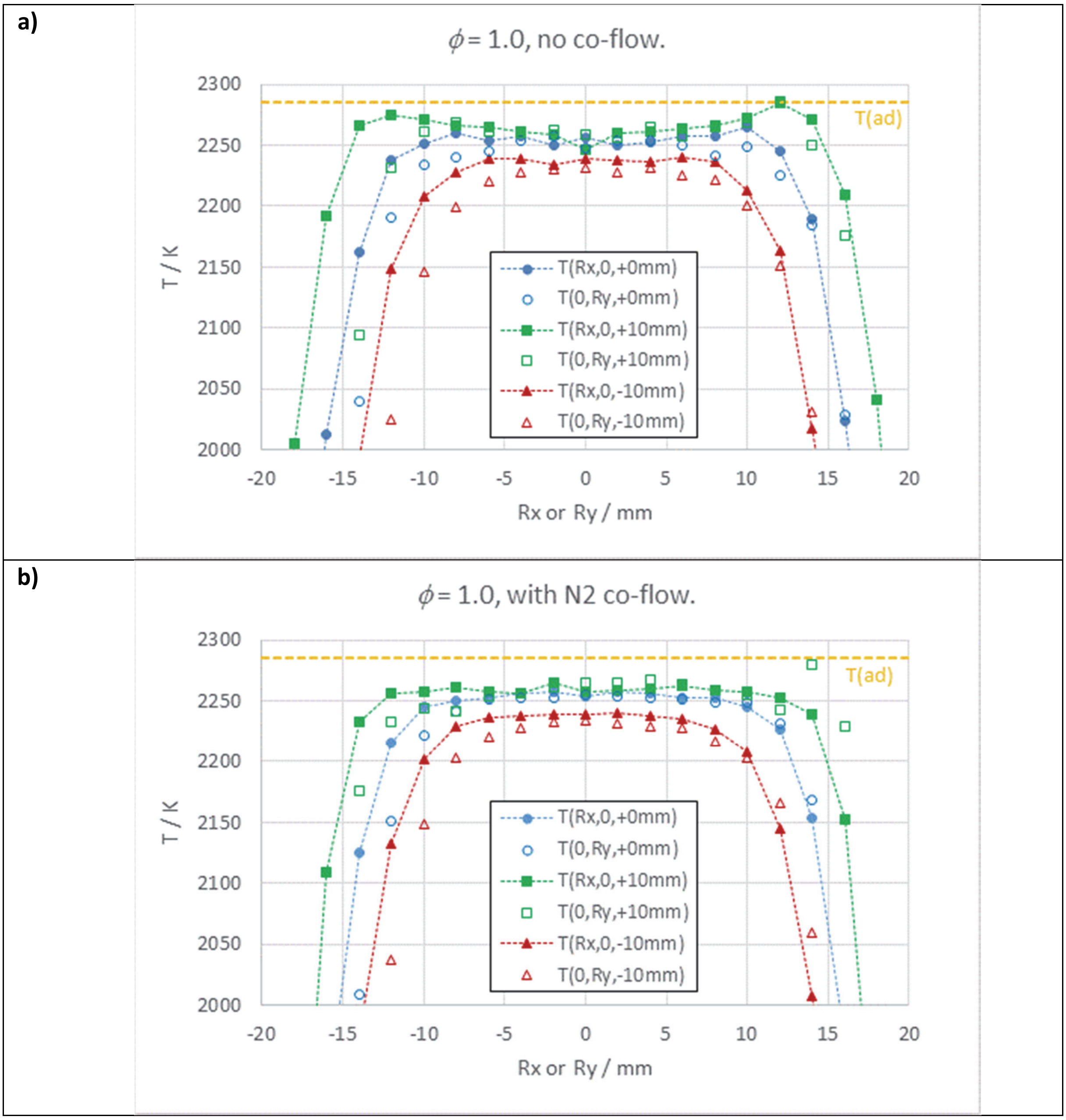


Figure 4.4 Post-flame temperature profiles a) without co-flow and b) with N_2 co-flow for $\phi = 1.0$, 23 SLPM airflow.

4.3.2 $\phi = 1.4$

Figure 4.5 shows the post-flame temperature profiles a) without co-flow and b) with N_2 co-flow, for $\phi = 1.4$, 23 SLPM airflow. The figure legend has the format $T(R_x, R_y, R_z)$, where R_x, R_y and R_z define the measurement position relative the burner datum, which, in this work is 20 mm above the centre of the burner. i.e. R_z = +0 mm, +10 mm and -10 mm corresponds to heights of 20 mm, 10 mm and 30 mm above the burner respectively and R_x and R_y are as defined in figure 4.3. The R_x profiles are shown as solid markers with dotted lines and the R_y profiles are shown with unfilled markers.

Measurements for R_z = +10 mm (10 mm above the burner) should be used with caution as it has been shown that the species may not have reached chemical equilibrium. Additionally, measurements for $|R_x|$ or $|R_y|$ greater than 15 mm may also be in error due to air mixing and the inherent assumptions used in the Rayleigh thermometry model. See Appendix 1 for tabulated results.

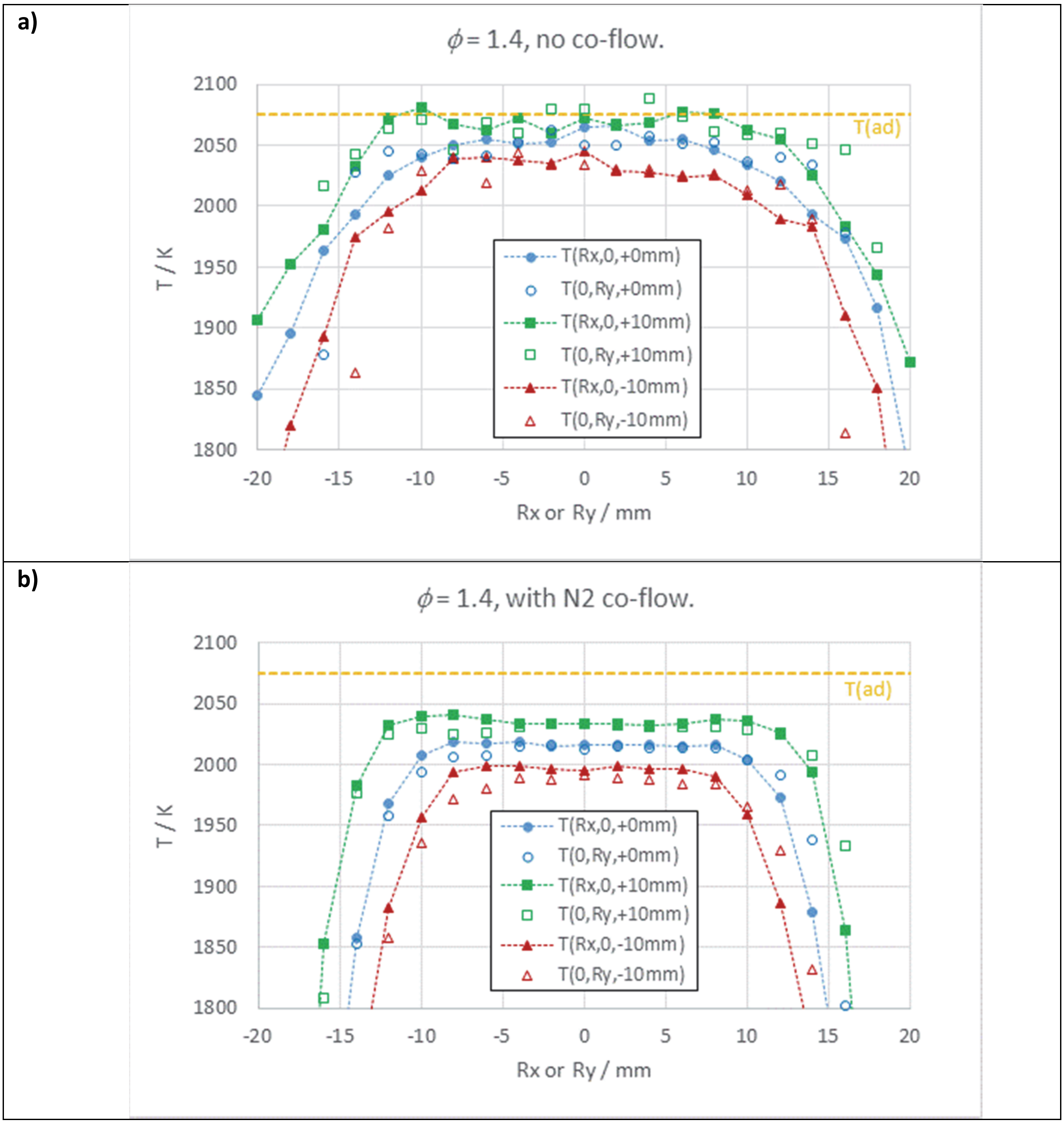


Figure 4.5 Post-flame temperature profiles a) without co-flow and b) with N_2 co-flow for ϕ = 1.4, 23 SLPM airflow.

4.3.3 $\phi = 0.8$

Figure 4.6 shows the post-flame temperature profiles a) without co-flow and b) with N_2 co-flow, for $\phi = 0.8$, 23 SLPM airflow. The figure legend has the format $T(R_x, R_y, R_z)$, where R_x, R_y and R_z define the measurement position relative the burner datum, which, in this work is 20 mm above the centre of the burner. i.e. R_z = +0 mm, +10 mm and -10 mm corresponds to heights of 20 mm, 10 mm and 30 mm above the burner respectively and R_x and R_y are as defined in figure 4.3. The R_x profiles are shown as solid markers with dotted lines and the R_y profiles are shown with unfilled markers.

Measurements for R_z = +10 mm (10 mm above the burner) should be used with caution as it has been shown that the species may not have reached chemical equilibrium. Additionally, measurements for $|R_x|$ or $|R_y|$ greater than 15 mm may also be in error due to air mixing and the inherent assumptions used in the Rayleigh thermometry model. See Appendix 1 for tabulated results.

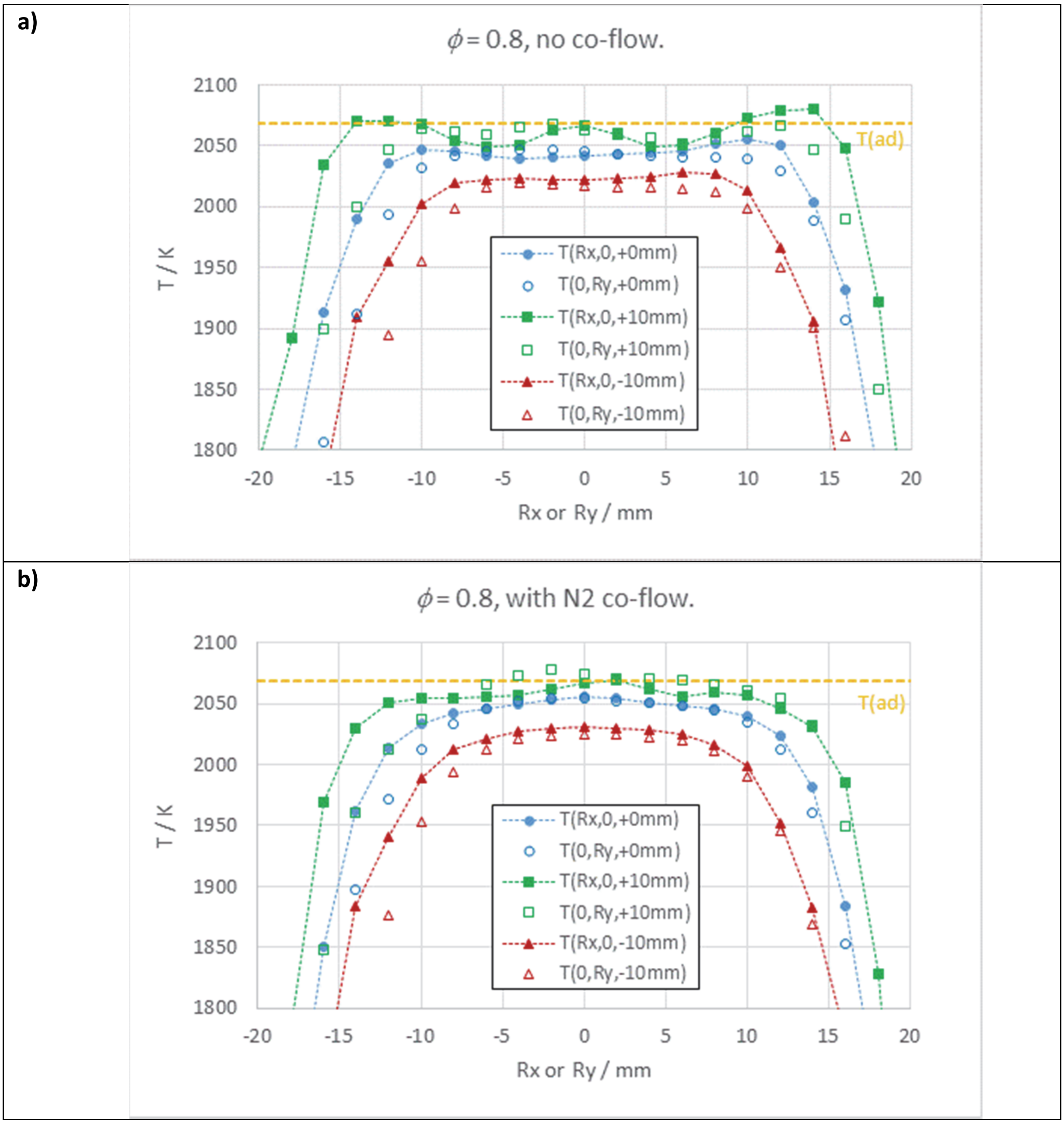


Figure 4.6 Post-flame temperature profiles a) without co-flow and b) with N_2 co-flow for $\phi = 0.8$, 23 SLPM airflow.

5 APPENDIX 1: TABULATED RESULTS

5.1 TEMPERATURE

5.1.1 Mean post-flame temperature 20 mm above the burner centre

ϕ	$T_f(\phi)$/ K	$\sigma(T)$ / K	$\sigma(T)$ / %	T_{ad} / K
0.8	2041.8	3.3	0.16	2068.3
0.9	2168.0	3.4	0.16	2201.8
1	2251.1	3.5	0.16	2285.5
1.1	2253.3	2.7	0.12	2287.1
1.2	2197.3	4.6	0.21	2226.6
1.3	2124.9	3.5	0.16	2151.4
1.4	2053.4	2.4	0.12	2075.2

Table 5.1 Mean post-flame temperature 20 mm above the burner for 10 days measurements. 23 SLPM airflow rate.

5.1.2 Change in post-flame temperature 20 mm above the burner centre

	$\Delta T_f(\phi)$ (re: mean of 10 tests) / K									
ϕ	1	2	3	4	5	6	7	8	9	10
0.8	2.8	5.6	-1.4	1.7	-3.6	-1.9	1.6	2.1	-1.9	-4.9
0.9	4.9	3.5	0.1	2.7	-4.8	-1.2	-0.8	1.4	-0.3	-5.6
1	4.5	3.4	5.6	-5.0	-3.4	-0.1	-0.2	-0.4	-0.7	-3.4
1.1	4.5	2.7	-3.0	0.9	-4.6	0.6	0.9	-1.4	0.8	-1.4
1.2	4.8	3.9	-6.4	-0.7	-4.2	6.1	3.5	-2.4	1.1	-5.7
1.3	2.7	5.1	2.2	-6.1	-3.4	2.6	0.4	1.6	-3.0	-1.9
1.4	3.6	3.5	-1.5	-2.3	-1.8	0.3	0.8	-0.6	1.7	-3.7

Table 5.2 Absolute change in post-flame temperature 20 mm above the burner centre for 10 days measurements. 23 SLPM airflow rate.

	$\Delta T_f(\phi)$ (re: mean of 10 tests) / %									
ϕ	1	2	3	4	5	6	7	8	9	10
0.8	0.14	0.27	-0.07	0.08	-0.18	-0.09	0.08	0.10	-0.09	-0.24
0.9	0.23	0.16	0.01	0.12	-0.22	-0.05	-0.04	0.06	-0.02	-0.26
1	0.20	0.15	0.25	-0.22	-0.15	-0.01	-0.01	-0.02	-0.03	-0.15
1.1	0.20	0.12	-0.13	0.04	-0.21	0.03	0.04	-0.06	0.04	-0.06
1.2	0.22	0.18	-0.29	-0.03	-0.19	0.28	0.16	-0.11	0.05	-0.26
1.3	0.13	0.24	0.10	-0.29	-0.16	0.12	0.02	0.08	-0.14	-0.09
1.4	0.17	0.17	-0.07	-0.11	-0.09	0.01	0.04	-0.03	0.08	-0.18

Table 5.3 Percentage change in post-flame temperature 20 mm above the burner centre for 10 days measurements. 23 SLPM airflow rate.

5.1.3 Temperature profiles with and without N_2 co-flow

	a) $T_f(R_x, 0, 0)$ / K						b) $\sigma\left(T_f(R_x, 0, 0)\right)$ / K					
	No co-flow			With N_2 co-flow			No co-flow			With N_2 co-flow		
R_x / mm	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8
-20	1623	1845	1592	1311	980	1459	205	88	179	243	222	187
-18	1772	1896	1788	1609	1285	1665	161	27	25	215	229	144
-16	2012	1964	1912	1916	1633	1850	72	24	45	115	131	64
-14	2162	1994	1989	2125	1858	1961	76	12	24	79	83	38
-12	2237	2025	2035	2215	1968	2014	22	17	17	29	37	17
-10	2252	2040	2046	2245	2008	2033	6	14	2	8	9	6
-8	2260	2051	2045	2250	2019	2042	6	15	2	3	5	2
-6	2253	2055	2041	2253	2017	2046	5	13	1	3	2	2
-4	2257	2051	2039	2256	2019	2049	8	10	1	3	7	1
-2	2251	2052	2041	2257	2015	2053	6	11	1	3	5	2
0	2256	2065	2042	2254	2016	2055	4	20	1	3	3	1
2	2250	2066	2043	2257	2016	2054	7	12	1	2	3	1
4	2253	2054	2044	2257	2016	2051	4	13	1	2	1	2
6	2257	2054	2046	2253	2015	2049	4	21	2	3	3	1
8	2258	2047	2051	2252	2016	2045	9	16	2	2	3	1
10	2265	2034	2055	2245	2004	2039	5	15	2	4	5	2
12	2245	2021	2050	2226	1973	2024	7	21	3	8	15	6
14	2190	1993	2003	2154	1878	1982	24	15	20	29	35	17
16	2023	1973	1932	1971	1704	1883	67	15	33	68	63	39
18	1826	1917	1778	1702	1441	1721	75	19	61	84	99	63
20	1528	1778	1467	1287	1007	1409	68	43	68	148	93	94

Table 5.4 Horizontal temperature profile in the R_x direction for $R_z = 0$ mm, 20 mm above the burner: a) Temperatures, b) Standard deviation of the measurements. Note: the SD's do not represent the uncertainty of the temperature measurement but can be used as an indicator of the flame stability.

	a) $T_f(R_x, 0, +10\ \mathrm{mm})$ / K						b) $\sigma\left(T_f(R_x, 0, +10\ \mathrm{mm})\right)$ / K					
	No co-flow			With N_2 co-flow			No co-flow			With N_2 co-flow		
R_x / mm	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8
-20	1791	1907	1790	1392	950	1482	161	65	143	253	6	30
-18	2005	1952	1892	1740	1415	1781	121	18	97	256	300	150
-16	2191	1981	2034	2109	1853	1969	64	26	50	133	58	69
-14	2266	2033	2070	2233	1983	2029	29	26	9	34	51	15
-12	2274	2073	2070	2256	2032	2050	9	20	3	8	11	9
-10	2271	2081	2067	2257	2040	2055	12	30	5	5	1	5
-8	2266	2068	2054	2261	2040	2055	15	33	6	7	1	5
-6	2265	2062	2049	2257	2037	2055	12	23	5	5	1	3
-4	2261	2072	2051	2256	2034	2057	13	23	2	6	1	2
-2	2259	2060	2063	2264	2033	2061	11	16	5	4	1	3
0	2246	2073	2066	2257	2033	2067	12	13	3	5	0	3
2	2260	2066	2058	2259	2033	2069	11	21	5	4	0	1
4	2261	2069	2049	2260	2033	2062	11	25	5	3	0	4
6	2263	2077	2050	2262	2034	2056	8	14	4	7	1	3
8	2266	2076	2061	2259	2037	2059	10	12	4	6	1	3
10	2272	2062	2072	2258	2035	2057	9	23	3	3	1	1
12	2285	2055	2079	2253	2026	2046	10	27	4	5	4	4
14	2271	2025	2080	2239	1994	2031	16	25	3	8	13	6
16	2210	1984	2048	2152	1864	1985	22	18	15	36	52	18
18	2040	1943	1922	1851	1532	1828	63	24	51	110	113	64
20	1740	1872	1691	1324	951	1500	114	54	90	135	153	132

Table 5.5 Horizontal temperature profile in the R_x direction for R_z = +10 mm, 10 mm above the burner: a) Temperatures, b) Standard deviation of the measurements. Note: the SD's do not represent the uncertainty of the temperature measurement but can be used as an indicator of the flame stability.

	a) $T_f(R_x, 0, -10\text{ mm})$ / K						b) $\sigma\left(T_f(R_x, 0, -10\text{ mm})\right)$ / K					
	No co-flow			With N_2 co-flow			No co-flow			With N_2 co-flow		
R_x / mm	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8
-20	1462	1710	1486	1090	833	1263	247	131	197	215	189	11
-18	1575	1819	1579	1427	1162	1502	128	77	70	203	209	125
-16	1794	1893	1773	1775	1510	1737	59	22	103	130	150	108
-14	1994	1974	1909	1976	1729	1883	85	22	36	74	80	17
-12	2149	1996	1955	2132	1883	1940	55	11	16	53	37	22
-10	2208	2013	2003	2202	1956	1989	27	18	21	24	26	18
-8	2228	2039	2019	2228	1993	2012	9	25	5	4	12	7
-6	2238	2040	2022	2236	1999	2021	7	22	2	4	6	3
-4	2239	2038	2023	2237	1999	2027	8	14	1	3	4	2
-2	2234	2035	2022	2239	1997	2030	9	14	1	3	3	1
0	2238	2045	2022	2238	1995	2031	9	14	0	2	5	1
2	2238	2028	2023	2241	1999	2030	9	16	1	4	4	1
4	2236	2028	2024	2237	1996	2028	6	19	2	4	3	1
6	2240	2024	2027	2235	1997	2024	7	14	1	2	4	2
8	2236	2025	2027	2227	1991	2016	7	13	1	4	6	3
10	2213	2010	2013	2208	1959	1999	13	16	8	10	12	8
12	2163	1990	1967	2145	1887	1951	25	16	19	23	30	14
14	2017	1983	1905	2008	1768	1883	69	22	27	59	47	27
16	1864	1910	1746	1826	1603	1775	73	25	75	63	79	41
18	1589	1850	1549	1542	1301	1551	99	31	96	98	97	80
20	1349	1653	1338	1378	1004	1238	76	90	96	118	122	104

Table 5.6 Horizontal temperature profile in the R_x direction for R_z = -10 mm, 30 mm above the burner: a) Temperatures, b) Standard deviation of the measurements. Note: the SD's do not represent the uncertainty of the temperature measurement but can be used as an indicator of the flame stability.

	a) $T_f(0, R_y, 0\ \mathrm{mm})$ / K						b) $\sigma\left(T_f(0, R_y, 0\ \mathrm{mm})\right)$ / K					
	No co-flow			With N_2 co-flow			No co-flow			With N_2 co-flow		
R_y / mm	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8
-20	1369	1061	1335	1126	953	1191	48	16	44	15	25	17
-18	1608	1392	1568	1478	1317	1500	75	211	131	201	205	172
-16	1805	1879	1806	1790	1645	1746	86	162	78	129	148	92
-14	2040	2028	1911	2009	1853	1898	159	65	36	140	70	23
-12	2191	2045	1993	2151	1958	1971	45	19	27	73	34	29
-10	2234	2042	2032	2222	1994	2012	13	4	10	15	11	16
-8	2240	2038	2042	2241	2006	2034	25	19	3	5	3	9
-6	2245	2041	2045	2251	2007	2045	21	17	2	2	4	3
-4	2254	2053	2046	2253	2015	2051	21	16	2	4	6	2
-2	2257	2063	2047	2253	2016	2054	10	13	1	1	3	1
0	2248	2050	2046	2255	2013	2054	18	17	1	3	2	1
2	2253	2050	2044	2254	2015	2052	10	17	1	4	2	1
4	2254	2058	2041	2252	2014	2050	9	12	2	2	6	2
6	2250	2051	2040	2251	2014	2048	17	17	1	3	7	1
8	2242	2052	2040	2248	2014	2044	9	16	2	11	5	1
10	2249	2036	2040	2248	2004	2034	6	16	4	29	5	5
12	2225	2041	2030	2231	1991	2012	9	30	9	57	9	10
14	2184	2034	1988	2168	1938	1960	22	134	16	52	24	23
16	2028	1979	1907	1994	1802	1852	62	75	32	60	51	40
18	1786	1785	1778	1738	1590	1700	128	83	54	91	77	55
20	1555	1359	1551	1397	1207	1385	72	277	101	111	123	105

Table 5.7 Horizontal temperature profile in the R_y direction for R_z = 0 mm, 20 mm above the burner: a) Temperatures, b) Standard deviation of the measurements. Note: the SD's do not represent the uncertainty of the temperature measurement but can be used as an indicator of the flame stability.

	a) $T_f(0, R_y, +10\ \mathrm{mm})$ / K						b) $\sigma\left(T_f(0, R_y, +10\ \mathrm{mm})\right)$ / K					
	No co-flow			With N_2 co-flow			No co-flow			With N_2 co-flow		
R_y / mm	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8
-20	1386	1186	1399	1005	916	1081	34	60	88	12	12	10
-18	1654	1713	1684	1513	1393	1536	141	300	136	330	324	293
-16	1924	2017	1899	1993	1808	1847	321	126	82	179	145	100
-14	2094	2042	2000	2176	1977	1960	287	27	58	55	49	49
-12	2232	2064	2047	2233	2024	2013	42	19	23	18	11	42
-10	2261	2071	2064	2244	2029	2037	11	20	5	22	1	28
-8	2269	2047	2062	2242	2025	2054	15	20	4	32	2	11
-6	2261	2068	2060	2254	2026	2066	18	11	4	33	1	4
-4	2260	2060	2066	2256	2031	2073	10	30	3	20	2	5
-2	2262	2079	2068	2261	2033	2078	11	31	6	7	1	3
0	2258	2080	2063	2265	2033	2075	15	21	3	9	0.4	3
2	2256	2067	2060	2265	2032	2071	11	35	3	4	1	2
4	2265	2088	2056	2267	2030	2071	15	16	4	7	1	4
6	2258	2073	2052	2263	2031	2069	5	26	6	5	3	4
8	2265	2061	2055	2259	2031	2065	37	23	4	3	1	4
10	2269	2059	2062	2255	2029	2061	61	26	8	5	2	4
12	2286	2060	2066	2242	2025	2054	76	28	25	7	2	23
14	2250	2051	2046	2279	2007	2032	29	28	17	189	7	43
16	2176	2046	1990	2230	1933	1949	33	34	21	324	31	47
18	1950	1966	1850	1928	1693	1740	98	34	56	271	89	72
20	1587	1494	1620	1308	1195	1236	137	179	82	156	148	151

Table 5.8 Horizontal temperature profile in the R_y direction for R_z = +10 mm, 10 mm above the burner: a) Temperatures, b) Standard deviation of the measurements. Note: the SD's do not represent the uncertainty of the temperature measurement but can be used as an indicator of the flame stability.

	a) $T_f(0, R_y, -10\ \text{mm})$ / K						b) $\sigma\left(T_f(0, R_y, -10\ \text{mm})\right)$ / K					
	No co-flow			With N_2 co-flow			No co-flow			With N_2 co-flow		
R_y / mm	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8	phi=1.0	phi=1.4	phi=0.8
-20	1277	1090	1250	1028	868	1055	63	22	77	13	67	24
-18	1475	1095	1424	1315	1213	1307	113	26	85	172	15	134
-16	1608	1459	1611	1633	1499	1598	96	206	65	144	150	128
-14	1791	1863	1767	1851	1723	1779	96	124	85	86	78	64
-12	2024	1982	1895	2038	1857	1876	69	91	36	93	49	33
-10	2146	2029	1955	2148	1936	1952	65	45	24	46	28	30
-8	2199	2040	1999	2204	1971	1994	36	58	16	14	9	13
-6	2220	2019	2016	2220	1980	2012	22	18	6	7	4	6
-4	2228	2044	2020	2228	1989	2020	11	9	1	3	8	2
-2	2230	2035	2018	2232	1988	2024	9	17	2	7	4	1
0	2231	2034	2017	2234	1991	2025	10	9	1	4	5	0.3
2	2228	2030	2016	2232	1989	2024	9	13	1	3	3	1
4	2231	2030	2016	2229	1988	2022	5	15	1	3	3	1
6	2226	2025	2015	2228	1984	2019	7	17	1	4	4	2
8	2221	2027	2012	2216	1983	2010	10	22	2	7	3	4
10	2201	2013	1998	2202	1965	1990	10	26	6	22	9	8
12	2152	2017	1950	2166	1929	1946	26	38	23	53	16	18
14	2031	1989	1901	2059	1831	1868	65	70	20	73	38	29
16	1791	1814	1811	1799	1709	1767	85	71	36	81	43	38
18	1619	1352	1622	1609	1469	1565	61	228	82	68	87	75
20	1424	1137	1431	1299	1098	1265	107	83	58	102	113	100

Table 5.9 Horizontal temperature profile in the R_y direction for R_z = -10 mm, 30 mm above the burner: a) Temperatures, b) Standard deviation of the measurements. Note: the SD's do not represent the uncertainty of the temperature measurement but can be used as an indicator of the flame stability.

5.2 SPECIES

The equilibrium species at $T_f(\phi)$ for an inlet temperature of 64 °C at P = 1 atm are calculated using GASEQ [1] using the *Equilibrium at defined T and P* solver. The results are given in Tables 5.10, 5.11 and 5.12, showing the mole fractions for the reactants, major and minor species respectively. The inlet temperature of 64 °C was the mean burner surface temperature (over all ϕ) measured with a calibrated thermal imager and it is assumed that the reactants are at this temperature when they exit the burner.

The major and minor post-flame species are also shown graphically in Figure 5.1.

	Mole fraction, inlet (reactants)			
ϕ	N_2	O_2	Ar	C_3H_8
0.8	0.755573	0.202705	0.009289	0.032433
0.9	0.752522	0.201887	0.009251	0.036340
1	0.749496	0.201075	0.009214	0.040215
1.1	0.746494	0.200270	0.009177	0.044059
1.2	0.743516	0.199471	0.009140	0.047873
1.3	0.740562	0.198678	0.009104	0.051656
1.4	0.737631	0.197892	0.009068	0.055410

Table 5.10 Mole fractions for reactants.

		Mole fraction, post-flame (Major species)						
ϕ	$T_f(\phi)$/ K	Ar	N_2	H_2O	CO_2	CO	O_2	H_2
0.8	2041.8	0.008987	0.729156	0.124322	0.093250	0.000885	0.037401	0.000251
0.9	2168.0	0.008898	0.722041	0.137392	0.101370	0.003492	0.019009	0.000923
1	2251.1	0.008781	0.713170	0.148468	0.103289	0.011694	0.005468	0.003117
1.1	2253.3	0.008603	0.699433	0.154460	0.093085	0.030830	0.000658	0.009475
1.2	2197.3	0.008394	0.682707	0.154816	0.078413	0.053482	0.000073	0.020225
1.3	2124.9	0.008188	0.666001	0.151511	0.066013	0.073361	0.000010	0.033801
1.4	2053.4	0.007990	0.649900	0.145719	0.056339	0.090122	0.000002	0.049222

Table 5.11 Mole fractions for post-flame species (major).

		Mole fraction, post-flame (minor)			
ϕ	$T_f(\phi)$ / K	OH	H	O	NO
0.8	2041.8	0.001845	0.000034	0.000176	0.003692
0.9	2168.0	0.002858	0.000142	0.000301	0.003572
1	2251.1	0.003034	0.000415	0.000272	0.002291
1.1	2253.3	0.001838	0.000732	0.000096	0.000791
1.2	2197.3	0.000852	0.000785	0.000023	0.000230
1.3	2124.9	0.000377	0.000664	0.000005	0.000070
1.4	2053.4	0.000170	0.000512	0.000001	0.000023

Table 5.12 Mole fractions for post-flame species (minor).

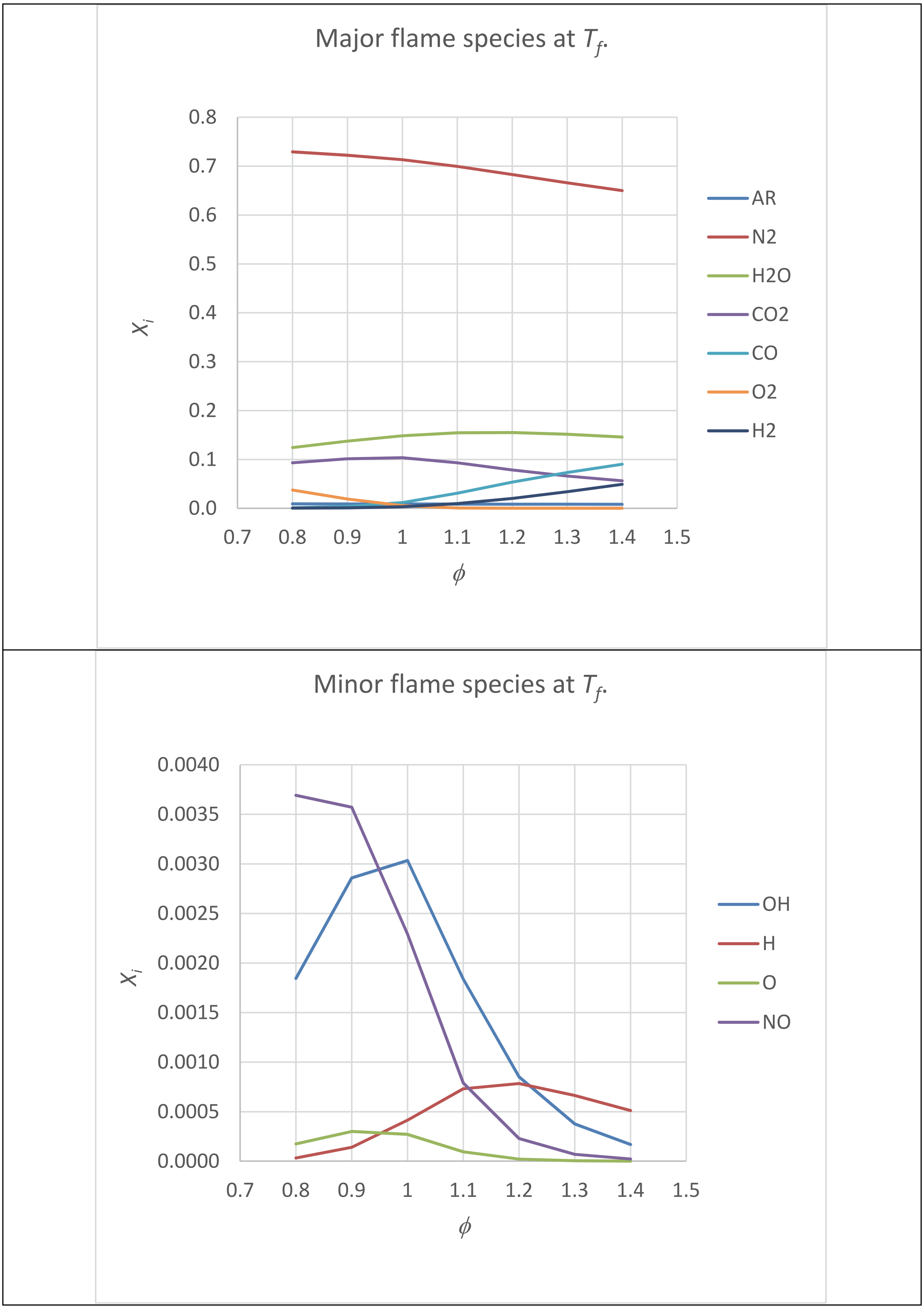


Figure 5.1 Major and minor post-flame species for the NPL STD flame.

6 APPENDIX 2: UNCERTAINTY BUDGET

Table 6.1 shows the uncertainty budget for the temperature measured 20 mm above the centre of the burner (R_z = 0 mm) using Rayleigh scattering Thermometry. For regions closer to the burner surface, where thermal and chemical equilibrium may not have been reached, and beyond ±15 mm horizontally from the central position, where the gas composition is uncertain, the uncertainties will be significantly larger.

Source	Type	Distr.	Size / ± %	Multiplier	Sensitivity. Coefficient	Size (1σ) / %
Molar refractivity data	B	Rect	0.20	0.58	1	0.12
Flow-meter uncertainty	B	Rect	1.00	0.58	0.1	0.06
Chemical equilibrium assumption	B	Rect	0.50	0.58	1	0.29
Air calibration PRT	A	Norm	0.05	1.00	1	0.05
Background scattered signal	A	Norm	0.10	1.00	0.5	0.05
Laser stability	A	Norm	0.05	1.00	1	0.05
Inlet air temperature (15-25 °C)	B	Rect	3.00	0.58	0.1	0.17
Atmospheric pressure	B	Rect	5.00	0.58	0.05	0.14
Gas purity	B	Rect	2.50	0.58	0.05	0.07
Flame temperature reproducibility	A	Norm	0.20	1.00	1	0.20
Total uncertainty (combined in quadrature)						**0.45 %**

Table 6.1 Uncertainty budget for the temperature 20 mm above the centre of the NPL STD flame.

7 APPENDIX 3: REFERENCES

1. *GasEq chemical equilibrium solver*, Chris Morley, http://www.gaseq.co.uk/

8 APPENDIX 4: NPL CONTACT DETAILS

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