



tessie User Manual

Urs Langenegger

ursslangenegger@gmail.com

*Paul Scherrer Institute
CH-5232 Villigen-PSI, Switzerland*

October 10, 2024

Abstract

This document provides an overview of the **tessie** software and is intended to provide all information required to install the **tessie** software and safely operate the coldbox for the CMS phase-2 pixel module testing. For future reference, the necessary hardware information is also included.

This document is work in progress. Please send all comments, in particular bug reports and complaints, to the email address given above. Many thanks!

Intended Use: **tessie**, together with the hardware, is designed to allow the safe operation of a coldbox with climatic chamber for thermal cycling and well-defined running conditions for testing the CMS phase-2 inner tracker (pixel) modules. Following the instructions in this user guide will provide any user the required knowledge and understanding to safely operate **tessie** and the coldbox.

Safety instructions: It is imperative, every time before operating the coldbox, to

- ensure that the N2 flow is connected to the coldbox and works according to plan (all throttles are open, no sharp bends in the tubing, etc).
- ensure that the chiller is turned on, that the filter inside the chiller is not clogged, and that water is flowing.

The user bears the responsibility for damage and accidents caused by (1) not reading and understanding this user guide or (2) modifying the coldbox hardware or deviating from the official build instructions.

Contents

1	Introduction	4
2	Hardware aspects	6
2.1	Raspberry Pi	6
2.2	CAN bus	6
2.3	TEC controller	7
2.4	Module probe card	8
2.5	Environmental monitoring with the Sensirion SHT85	8
2.6	CAN controlled FRAS/4 Relays	8
2.7	Lid-closure sensor	10
2.8	Cross section of module cooling infrastructure	10
3	Installation	13
4	Upgrading tessie or the TEC firmware	21
4.1	tessie upgrades	21
4.2	TEC firmware upgrades	22
5	Operational aspects	23
5.1	GUI - Raspberry Pi touchscreen interface to tessie	23
5.2	Web interface to tessie	25
5.3	MQTT - direct text-based communication with tessie	25
5.4	Safe operations limits	28
5.5	First steps	28
5.6	Direct readout of probe card	29
5.7	Traffic Lights	30
5.8	Alarm channels	30
5.9	Modes for cooling the TECs	30
5.10	Temperatures on the TEC and module	30
6	Frequently asked questions	33
6.1	Operations	33
6.1.1	Do's and don'ts	33
6.1.2	tessie does not start	33
6.1.3	An alarm goes off if I plug in a module and close the lid	34
6.1.4	Alarm module temperature exceeds SAFETY_MAXTEMPM (single module) .	34
6.1.5	Alarm module temperature exceeds SAFETY_MAXTEMPM (single module) .	34
6.1.6	Alarm module temperature exceeds SAFETY_MAXTEMPM (many modules) .	35
6.1.7	The CANbus shows many errors	35
6.1.8	Persistent issue with a single TEC	35
6.1.9	Where is the printout/logfile/CSV file from tessie?	35
6.1.10	The N2 flow valves are not working, but no CANbus errors appear .	36
6.2	Installation	36
6.2.1	The touchscreen is white	36
6.2.2	The touchscreen gradually turns white and stays white.	36

6.2.3	Server certificate verification	36
6.2.4	How to test the USB loudspeaker and <code>tessie</code> audio alarms	37
References		38

1 Introduction

The **tessie**¹ program controls all aspects of the safe operation of the PSI coldbox developed for the testing of the CMS phase-2 pixel modules. It is hosted in a github repository [1].

tessie is a multi-threaded C++ program running on the Raspberry Pi with a custom hardware “hat” inside the coldbox. Originally, it started as a Qt5 GUI (graphical user interface) and it can still be operated in that way. However, in a production setup, it is mostly controlled through a web interface and/or scripts. The threads in **tessie** control, respectively, the graphical display, the underlying hardware (CAN [2] and I2C [3] bus), and the MQTT messaging service [4]. The web interface is driven by a node.js webserver (**tessieWeb**), running on the Raspberry Pi and listening to the MQTT messages and operating **tessie** through MQTT.

The coldbox, sketched in Fig. 1, comprises eight positions, where TEPX modules can be positioned in thermal contact to Peltier elements, each controlled by custom TEC controllers (TEC is the abbreviation for ThermoElectric Cooler and a synonym for Peltier element). A centrally placed PCB accommodates the electrical connections and readout of the TEPX modules and furthermore hosts an SHT85 air and humidity sensor [5].

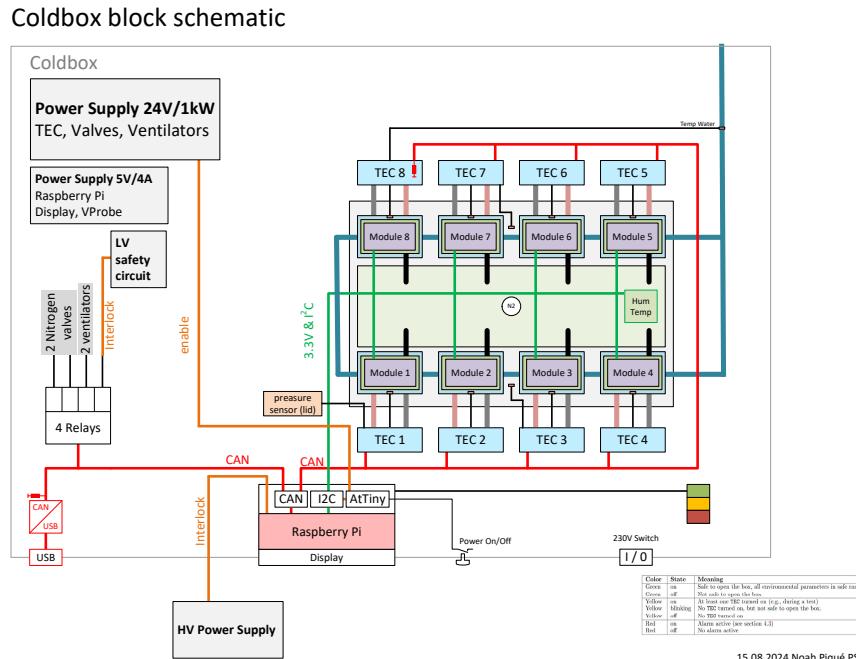


Figure 1: Sketch of the PSI coldbox showing the orientation and numbering scheme of the eight module positions, the CAN bus and I2C bus connection scheme, and the FRAS/4 Relays controlling the N2 flow. The three white boxes above the Raspberry Pi are implemented using a custom “hat”. The thick blue line exiting at the top right indicates the water pipe to the chiller. Note that TEC numbering starts at 1, not 0 (zero). Figure from Ref. [6]

tessie enforces a safe operation environment in the coldbox. It will shutdown operations

¹Etymology: tessie sounds better than TC (box), for temperature cycling (box)

if certain environmental parameters leave the safe region (cf. section 5.4). It will inhibit turning on the TECs if the chiller is not running (**FIXME**: currently only approximately true!) In addition, a watchdog process on the Raspberry Pi ensures that `tessie` is running and performing its required tasks (**FIXME**: This will be implemented in the near future!).

The coldbox can be operated in a manual direct manner and through scripts. Manual direct operation at the box includes for example

- Opening and closing the lid to load or unload modules for testing
- Turning on/off the N2 flow controls via the GUI on the touchscreen.

The normal user interaction proceeds through a web interface and any browser².

In addition, it may be required to log into the coldbox Raspberry Pi using `ssh` to update and recompile the code and/or restart the `tessie` program and/or its webserver.

²Not tested on Edge or Internet Explorer. If you encounter problems with Edge, please let us know.

2 Hardware aspects

2.1 Raspberry Pi

The coldbox is operated with a Raspberry Pi Model 4B. Table 1 provides an overview of **tessie**'s pin usage of the J8 connector on the **Raspberry Pi** (*cf.* the result of the `pinout` command issued on the **Raspberry Pi**).

Table 1: **Raspberry Pi** pins (physical and GPIO numbering scheme) used by **tessie**.

phys.	GPIO	Name	Remarks
11	17	GPIORED	red light of traffic light
13	27	GPIOYELLO	yellow light of traffic light
15	22	GPIOGREEN	green light of traffic light
16	23	GPIOINT	interlock for external usage (HIGH = safe for operation)
18	24	GPIOPSUEN	always HIGH (not used to date)

A custom-made "hat" provides the interface between the **Raspberry Pi** and the CAN/I2C buses. The CAN bus provides the communication link to the TECs and the FRAS. The I2C bus allows the readout of the SHT85 sensor and the module probe card. However, because that "hat" has no direct consequences for **tessie**, it is not discussed further here.

2.2 CAN bus

Communication in the CAN bus proceeds through the transfer of frames, consisting (among others) of an ID (identifier), specifier of the data length (in our system: 0, 1, or 5), and the data. Any connected device can transmit data when the bus is free. All connected devices see all transmissions and decide whether or not to accept it, based on the board identifier and one specific bit in the ID. The ID consists of 11 bits illustrated in Fig. 2. Starting at

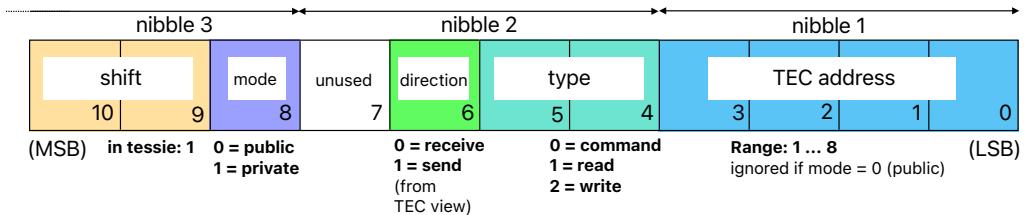


Figure 2: The CAN ID used in the coldbox's CAN bus.

the least-significant bit (LSB), 4 bits are required to encode the TEC ID because the first TEC has address 1 (not 0). This fact is utilized in the MQTT communication where address 0 corresponds to "all" TECs. The next two bits encode whether the frame contains a read (type = 1) or write (type = 2) request, or a command (type = 0). Bit 6 encodes the direction of the communication, as seen from the TEC. Bit 7 is not used. Bit 8 determines whether the

communication is targeted at a specific address (mode = 1) or is a broadcast (mode = 0). The two most significant bits (MSB) are used for a potential address space offset and are set to 0x01. A few remarks:

- Every nibble of the CAN ID has a range <0xA because (1) there are only 8 TECs, (2) bit 7 is not used (and set to 0), and (3) there are only 2 bits in the third nibble.
- The TEC address is immediately visible in the `candump` printout in the first digit of the displayed address
- The FRAS frames (emitted and received by the FRAS) follow a different bit-encoding scheme, *cf.* subsection 2.6.

The CAN bus traffic can be easily monitored with the `candump` tool:

```
pi@coldbox02:~ $ candump can0
can0 210 [1] 01
can0 251 [5] 01 00 00 00 00
can0 252 [5] 01 00 00 00 00
can0 253 [5] 01 00 00 00 00
can0 254 [5] 01 00 00 00 00
can0 255 [5] 01 00 00 00 00
can0 256 [5] 01 00 00 00 00
can0 257 [5] 01 00 00 00 00
can0 258 [5] 01 00 00 00 00
can0 210 [1] 02
.. snip ..
can0 318 [1] 08
can0 358 [5] 08 00 4C BB 41
can0 311 [1] 08
can0 351 [5] 08 00 C3 27 3F
can0 210 [1] 09
.. snip ..
can0 318 [1] 0A
can0 358 [5] 0A 00 F6 90 BF
.. snip ..
can0 042 [0]
can0 040 [1] 03
.. and so on ..
```

A short explanation of the this printout:

- The first column shows the CAN bus, the second the CAN ID, the third the length of the data block, and the fourth (if present) the data.

2.3 TEC controller

The TEC controllers are a central element of the coldbox and allow the direct or automated (PID) control of the TECs, in addition to their powering and monitoring. A coldbox houses 8

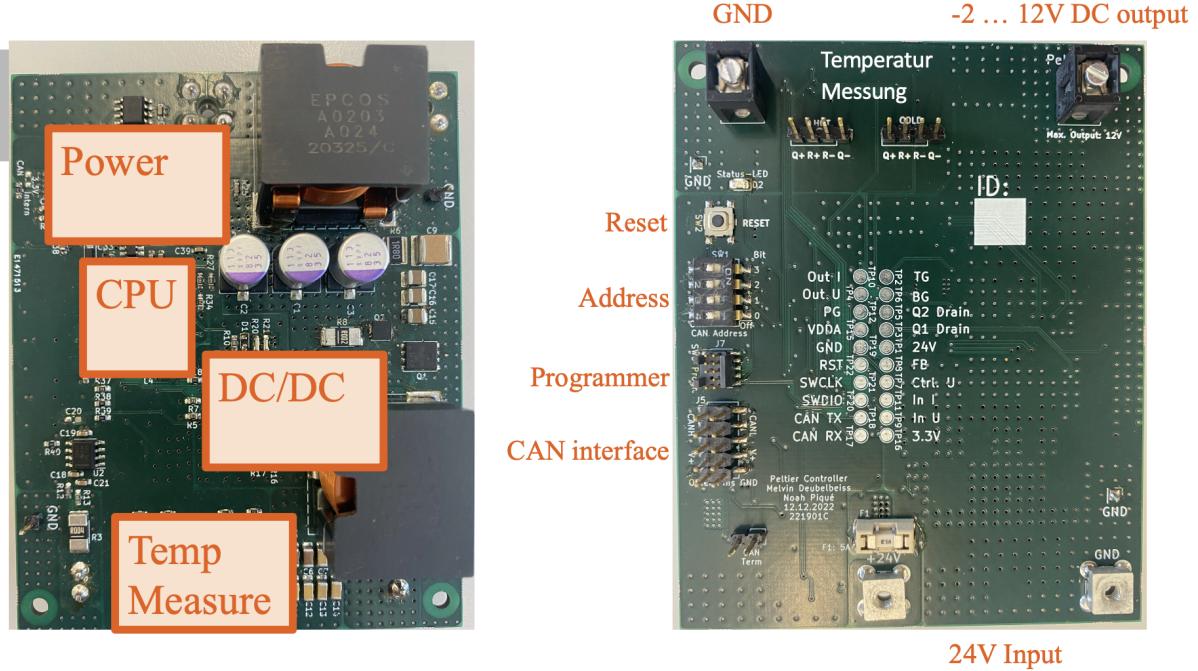


Figure 3: Photo of the (left) frontside and (right) backside of the TEC controller [6]. The fuse F1 is visible on the backside.

TEC controllers, one for each module position. The TEC controllers are attached to the CAN bus and have board IDs (addresses) 1...8. Controlling and obtaining the status of the TEC controllers is achieved through control commands and through writing to and reading values from various registers, provided in Table 2.

FIXME: List all registers, commands, etc.

2.4 Module probe card

The module probe card [7], illustrated in Fig. 4 and sometimes referred to as "Vprobe" below, is used to measure voltage levels on test points on all four chips of a module. Since its readout is connected to the coldbox I2C bus, `tessie` is used to obtain the readings of this probe card.

2.5 Environmental monitoring with the Sensirion SHT85

The SHT85 sensor [5] is read out in the high-repeatability mode. The I2C device address of the sensor is 0x44. The data transferred consist of 2×2 bytes together with 2 bytes for a CRC checksum.

2.6 CAN controlled FRAS/4 Relays

To steer the two N2 valves, the ventilator, and to provide a second interlock signal for the module low-voltage Schütz, a "CAN Output FRAS4 4x Relais Out" device is connected to the CAN bus [8]. We refer to this device as "FRAS" in the following. Its baud rate

Table 2: TEC Registers and commands. The flash variables are indicated with (F).

Register	Name	Type	Description
0	Mode	R/W (UInt32)	0=ConstTemp(PID) 1=ConstVoltage(manually)
1	ControlVoltage_Set	R/W (Float)	Setting the output peltier voltage
2	PID_kp	R/W (Float) (F)	PID loop parameter
3	PID_ki	R/W (Float) (F)	PID loop parameter
4	PID_kd	R/W (Float) (F)	PID loop parameter
5	Temp_Set	R/W (Float)	Target Module temperature
6	PID_Max	R/W (Float) (F)	Max. output Peltier voltage
7	PID_Min	R/W (Float) (F)	Min. output Peltier voltage
8	Temp_W	R (Float)	Water temperature
9	Temp_M	R (Float)	Module temperature
10	Temp_Diff	R (Float)	Temperature difference
11	Peltier_U	R (Float)	Voltage applied to Peltier element
12	Peltier_I	R (Float)	Current through Peltier element
13	Peltier_R	R (Float)	Resistance in Peltier element
14	Peltier_P	R (Float)	Power consumption of Peltier element
15	Supply_U	R (Float)	Voltage applied to TEC controller
16	Supply_I	R (Float)	Current through to TEC controller
17	Supply_P	R (Float)	Power consumption of TEC controller
18	PowerState	R (UInt32)	0=Off, 1=On
19	ErrorState	R (UInt32)	See dedicated error code table
20	Ref_U	R (Float) (F)	Reference voltage (ADC/DAC)
Address	Command	Type	Description
0	No_Command	Command	Nothing
1	Power_On	Command	Turn on TEC
2	Power_Off	Command	Turn off TEC
3	Watchdog	Command	Send every <3 seconds
4	Alarm	Command	With Errorcode from TEC to master
5	Clear_Error	Command	
6	Get_SW_Version	Command	Returns TEC firmware version
7	Save_Variables	Command	Saves all variables into flash memory
8	Load_Variables	Command	Loads all variable from flash memory
255	Reboot	Command	

should be at 125 kbits/s (default setting when delivered), following the instructions in the datasheet. The CAN bus ID (module address) should be set to 0/8 with the "top"/"bottom" rotary switches. This setting corresponds to module address $0x4y$, where $y = 0/1/2$ for process/service/control frames, respectively. The FRAS must receive (service) frames with a time interval smaller than three seconds. **tessie** sends such a frame every second. In case the FRAS is active, **tessie** sends a *process* frame every second.

2.7 Lid-closure sensor

FIXME

4200 when open, something else (possibly negative) when closed. To be seen.

2.8 Cross section of module cooling infrastructure

The cross section of the module cooling infrastructure is shown in Fig. 5. A few remarks may be useful.

- The PT1000 providing the temperature reading for the TEC register called Temp_M is not in thermal contact with the module but rather with the TEC (the Peltier module).
- The module has a thermal power of about 10-12 W (after accounting for voltage drops between the power supply and the module). This implies that the temperature on the module is substantially higher (of the order 15-20°C) on the module than the TEC. This is discussed and illustrated in Fig. 12 in section 5.10.

Module Probe V2

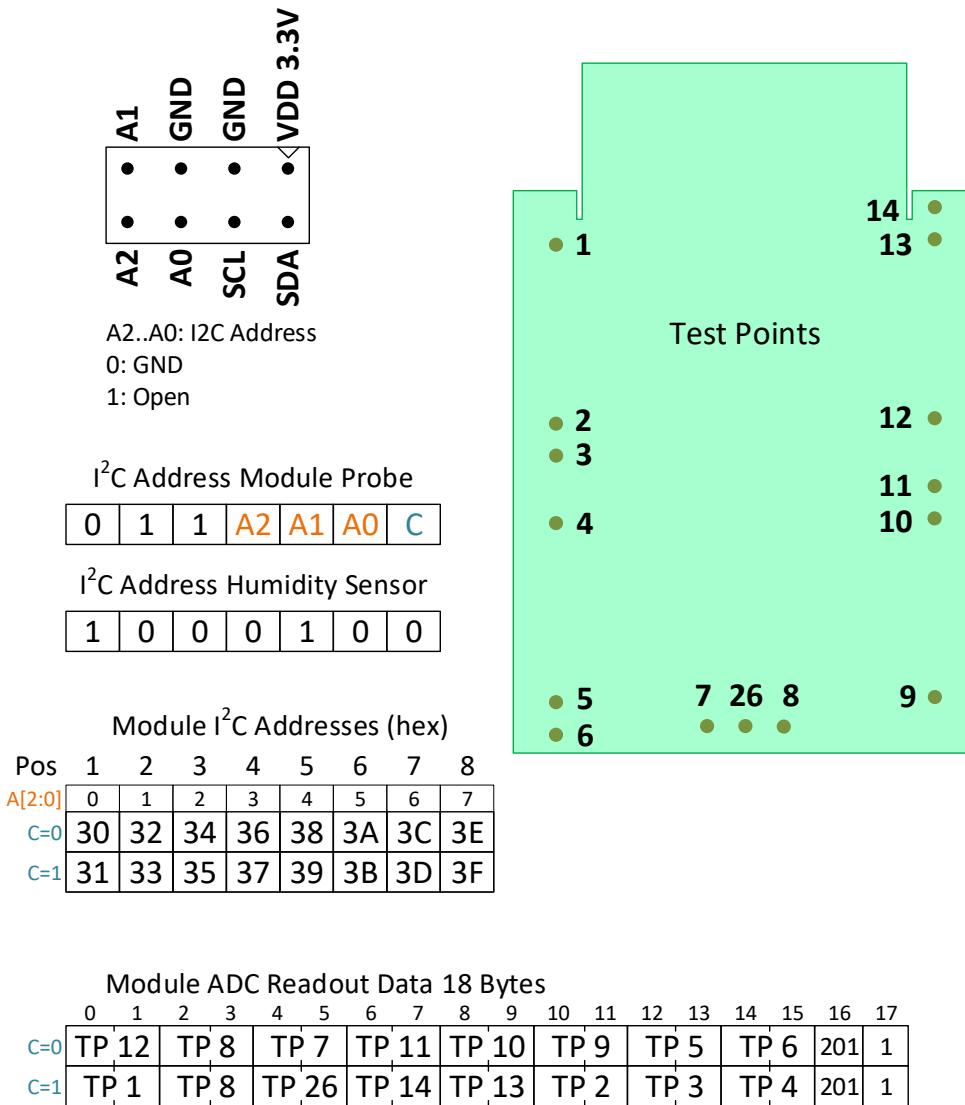


Figure 4: Module probe card documentation [7]. Note that $V_{DD} = 3.3114$, with a permille-level variation between boards. In the readout, bytes 16 have the value 201 as cross-check, and bytes 17 indicate the software version of the board.

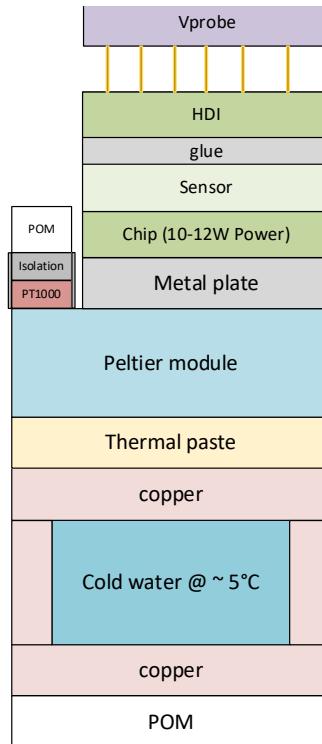


Figure 5: Cross section of the cooling infrastructure for a single module inside the coldbox. From the top: "Vprobe" is the probe card (subsection 2.4), the structures from the "HDI" down to and including the "Chip" represent the module, positioned on a metal plate in direct contact to the TEC (Peltier module). The cold water from the chiller is circulating in a copper enclosure. Note the placement of the PT1000 measuring the "Temp_M" register of the TEC controller: despite its name, it does *not* measure the module temperature but rather the TEC temperature of the module!

3 Installation

We assume that you have a coldbox where the hardware is completely configured according to the instructions [9] and connected to the internet. In this section we describe how to prepare the Raspberry Pi, starting from creating its boot device, installing all required software components, and setting up the automatic `tessie` startup at boot time.

A few important remarks before describing the installation procedure.

- If the Raspberry Pi’s screen turns white (at the end of the boot process) very likely the screen flatband connector is not properly inserted. This can happen easily when inserting the SD card.
- It has been observed that a few power-cycles are required to have the touchscreen work properly (instead of displaying “nothing”, which can mean a white screen or a black screen). Alternatively, try to connect via ssh and do (in a terminal) `sudo shutdown -r now`. Note that “nothing” is not the same as the white screen indicating a flatband cable-connector issue.

It seems that this issue is due to newer releases of Debian version 12 (bookworm) in image files dated 2024-03-13 and 2024-03-15. It is not present in the image file dated 2023-12-05, referred to below.

- The following instructions have been tested verbatim (line by line copy-paste) with a Raspberry Pi 4 Model B Rev 1.4 with 8 GB RAM. Please provide feedback if you run into problems with a different Raspberry Pi.
- There is a script-based installation procedure provided by Branislav (Bane) Ristic at his [forked repository](#). Depending on the image you start with, his setup may work well for you. It should be rather straightforward to merge that branch with the `master` branch of the main `tessie` repository since it is only about installation.

Installing `tessie` is straightforward, if the following steps are followed.

- Using the ”Rasberry Pi Imager” [10], available for macOS, Windows, and Linux, burn a SD card with the 2023-12-05 image file, available from [here](#). Make sure that you do *not* use XZ utils versions 5.6.0 or 5.6.1 since they contain malicious code (cf. [link](#)).

It is recommended to apply a few changes to the default setup as illustrated in Fig. 6, in particular set the user name and password, the hostname, and allow `ssh` access for remote work; this is available from the Imager after you have specified the model, the OS, and the storage device (the SD card).

- Insert the SD card into the foreseen slot beneath the touchscreen flatband cable connector and power up the Raspberry Pi, i.e., plug in the (USB-C) power cable. If the touchscreen goes white, it is likely due to the ”big” flatband connector not being plugged in correctly. Try again.

On its first power-up, the Raspberry Pi will reboot various times. Be patient.

At the end of the startup/boot sequence you should see a bluish background image showing a cormorant fisherman of Guilin, China.

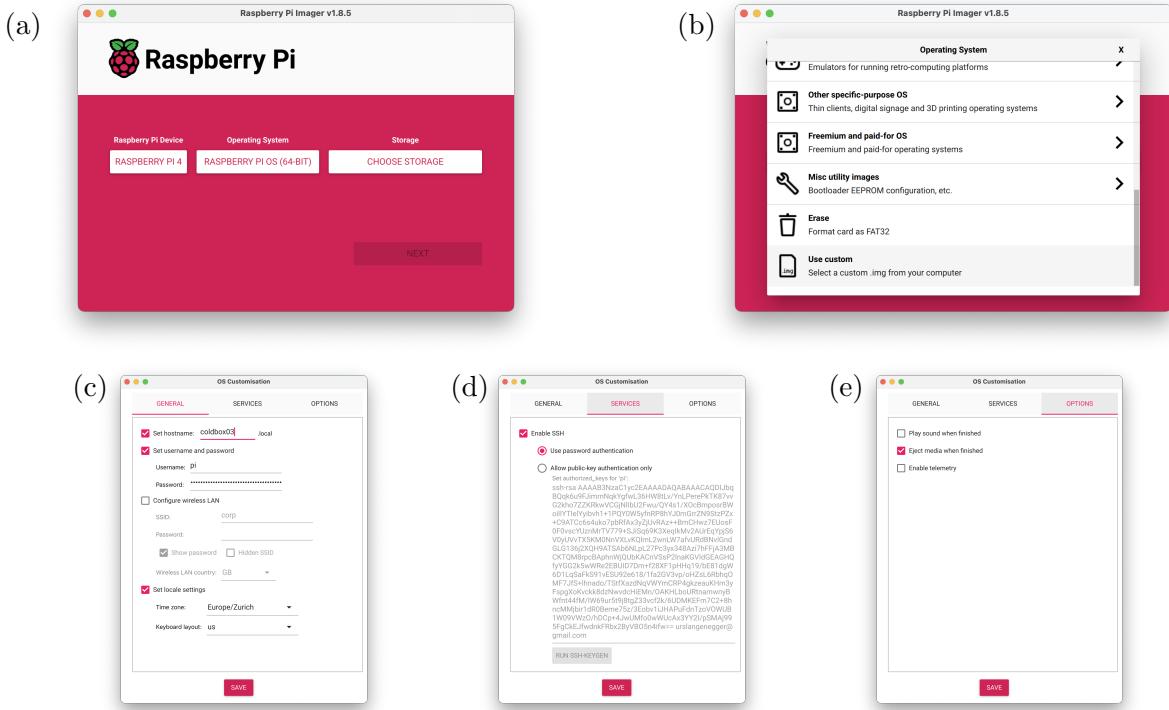


Figure 6: Screen shot of the Raspberry Pi Imager and customization examples. (a) Select the model and OS, (b) choose ‘EDIT SETTINGS’ to reach the lower panels, (c) enter the hostname and set a password for the default user ‘pi’ (use this!), (d) enable ssh connections, (e) if you want.

- *Installation of dependencies*

Open a terminal (it should be accessible from one of the icons at the top of the display) or, better, login from another computer using `ssh` and do the following:

```
sudo date -s "Wed Apr 17 2024 10:00:00"

sudo apt-get update

sudo apt install -y nodejs
sudo apt install -y npm

sudo apt-get install -y libmosquitto-dev libmosquittopp-dev
sudo apt install -y mosquitto mosquitto-clients

sudo apt install -y libqt5charts5 libqt5charts5-dev

sudo apt-get install -y nginx

sudo apt-get install -y cmake libusb-1.0
```

Do enter the correct day, date, and time in the first line above. Else you will get “server certificate verification” failures further down and other issues will arise.

- *Installation of tessie*

Get the `tessie` software and compile it:

```
cd /home/pi
git clone https://github.com/ursl/tessie.git
cd tessie/src
qmake -o Makefile tessie.pro
make -j2
```

Note 1: It is not recommended to use more than 2 cores for the compilation (“-j2”) because of potential memory shortages.

Note 2: In case you want to compile `tessie` on a non-Raspberry Pi host without I2C/CAN bus, invoke `qmake "CONFIG+=NOPI" -o Makefile tessie.pro`.

- *Mosquitto setup*

Using the `nano` editor in `sudo` mode, *i.e.*, `sudoedit` in a vanilla system, edit the file `/etc/mosquitto/mosquitto.conf` and add the following two lines to the end of the file:

```
listener 1883
allow_anonymous true
```

In case the above instructions are unclear, the following is what you should type into the terminal: `sudoedit /etc/mosquitto/mosquitto.conf`, jump to the end, insert the two lines, and exit the editor (using in sequence: `CTRL-x y RET`).

- *Hardware (I2C and CAN) bus configuration*

Using `sudoedit`, edit the file `/boot/firmware/config.txt` to contain the following two lines:

```
dtparam=spi=on
dtoverlay=mcp2515-can0,oscillator=12000000,interrupt=25
dtoverlay=spi-bcm2835-overlay
dtparam=i2c_vc=on
```

- *tessie webserver*

Setup the tessie web server by installing all required node packages

```
cd /home/pi/tessie/node/test1
npm install --save express socket.io mqtt
```

- *tessie and related services startup at boot time*

With `sudoedit` create the file `/lib/systemd/system/tessie.service` with the following content (i.e. do `sudoedit /lib/systemd/system/tessie.service` and copy-paste the following):

```
[Unit]
Description=tessie
After=network.target

[Service]
Type=idle
User=pi
Group=staff
Environment="XAUTHORITY=/home/pi/.Xauthority"
Environment="DISPLAY=:0"
WorkingDirectory=/home/pi/tessie/src
ExecStartPre=/home/pi/tessie/resetCAN.sh
ExecStart=/home/pi/tessie/src/tessie -f
StandardOutput=inherit
StandardError=inherit
Restart=on-failure
RestartSec=2s

[Install]
WantedBy=graphical.target
```

Note that `tessie` is run under the user `pi`. For the tessie webserver do `sudoedit /lib/systemd/system/tessieWeb.service` with the following contents

```
[Unit]
Description=tessie
```

```
After=multi-user.target
```

```
[Service]
Type=idle
WorkingDirectory=/home/pi/tessie/node/test1
ExecStart=/usr/bin/node /home/pi/tessie/node/test1/server3.js

[Install]
WantedBy=multi-user.target
```

FIXME A description of the watchdog service and its installation will follow in due time.

- *Configure nginx*

This **optional section** allows connecting to `http://coldbox03` instead of `http://coldbox03:3000`. Create the `nginx` configuration file with the command `sudoedit /etc/nginx/sites-available/default` and replace the contents of the file with the following contents

```
server {
    listen 80;
    server_name coldbox03.psi.ch;

    location / {
        proxy_pass http://localhost:3000;
        proxy_http_version 1.1;
        proxy_set_header Upgrade $http_upgrade;
        proxy_set_header Connection 'upgrade';
        proxy_set_header Host $host;
        proxy_cache_bypass $http_upgrade;
    }
}
```

Do change `coldbox03.psi.ch` to your coldbox hostname and domain! Be careful when copy-pasting the inverted commas! Start the service with

```
sudo service nginx start
```

- *Configure sound*

This extremely important section provides information on how to enable sound output to an attached USB loudspeaker. First determine which sound card your loudspeaker is attached to with

```
cat /proc/asound/cards
```

This will result in a list similar to

```

0 [vc4hdmi0      ]: vc4-hdmi - vc4-hdmi-0
                      vc4-hdmi-0
1 [vc4hdmi1      ]: vc4-hdmi - vc4-hdmi-1
                      vc4-hdmi-1
2 [Headphones     ]: bcm2835_headpho - bcm2835 Headphones
                      bcm2835 Headphones
3 [UACDemoV10    ]: USB-Audio - UACDemoV1.0
                      Jiel Technology UACDemoV1.0 at usb-0000:01:00.0-1.3, full speed

```

Here the loudspeaker is attached to card 3. With this information `sudoedit` the file `/etc/asound.conf` with the contents

```

defaults.pcm.card 3
defaultsctl.card 3

```

You should make sure that the USB loudspeaker works and is easily audible (cf. section [6.2](#) for instructions if necessary)

- *Startup services*

Now enable the startup of the two low-level components at boot time plus tessie and its webserver

```

sudo systemctl enable pigpiod
sudo systemctl enable mosquitto.service

```

```

sudo systemctl enable tessie.service
sudo systemctl enable tessieWeb.service

```

You can always monitor the status of these "services" with

```

systemctl status tessie
systemctl status tessieWeb

```

- *Hardware power button configuration*

Download the auxiliary software package and install it:

```

cd /home/pi
git clone https://github.com/Howchoo/pi-power-button.git
./pi-power-button/script/install

```

Warning: If you do this step on a Raspberry Pi that is *not* in a coldbox with a central power button, it will likely shutdown down and not properly power up!

- *Splash screen configuration*

(Note: This is not compulsory. There is no real need to change the splash screen.)

Using `sudoedit`, edit the file `/boot/firmware/cmdline.txt` to contain *on one line* the following two lines (they are provided here on two lines such that they can be copied in their entirety):

```
console=serial0,115200 console=tty1 root=PARTUUID=7a0cea11-02 rootfstype=ext4
fsck.repair=yes rootwait quiet splash plymouth.ignore-serial-consoles
```

Using `sudoedit`, edit the file `/boot/firmware/config.txt` to contain

```
disable_splash=1
```

Enter the following in a terminal:

```
cd /usr/share/plymouth/themes/pix/
sudo mv splash.png splash.png.bac
sudo cp /home/pi/tessie/splash.png ./
```

Now reboot the system, e.g., with `sudo shutdown -r now`. If the shutdown process gets stuck, hit the central power button. If all goes well, the touchscreen of the Raspberry Pi will show the GUI featured in Fig. 7. You can connect from any PC.

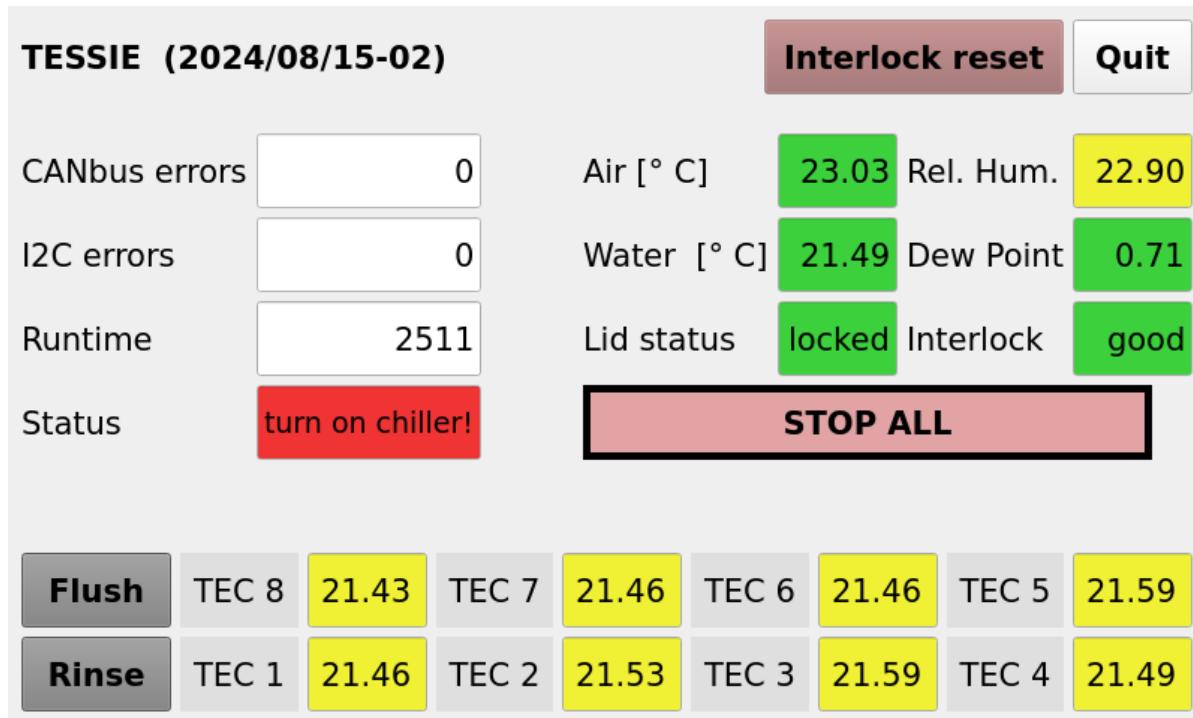


Figure 7: The GUI appearing on the Raspberry Pi touch screen. The interaction possibilities are limited to (1) controlling the N2 flow with **Rinse** and **Flush**, (2) stop operations with "STOP ALL" which will turn off all TECs, turn on maximal N2 flow by opening both the rinse and flush valves, and breaking the HV/LV interlocks, (3) resetting the interlocks, and (4) "Quit"-ing the program. The **Rinse** and **Flush** buttons will have a greenish background color when these valves are open and N2 is flowing. For full control of **tessie** you should use the web interface shown in Fig. 8.

The normal manual way to interact with **tessie** is through a webbrowser. Point your favorite browser to <http://coldbox03>, cf. Fig 8.

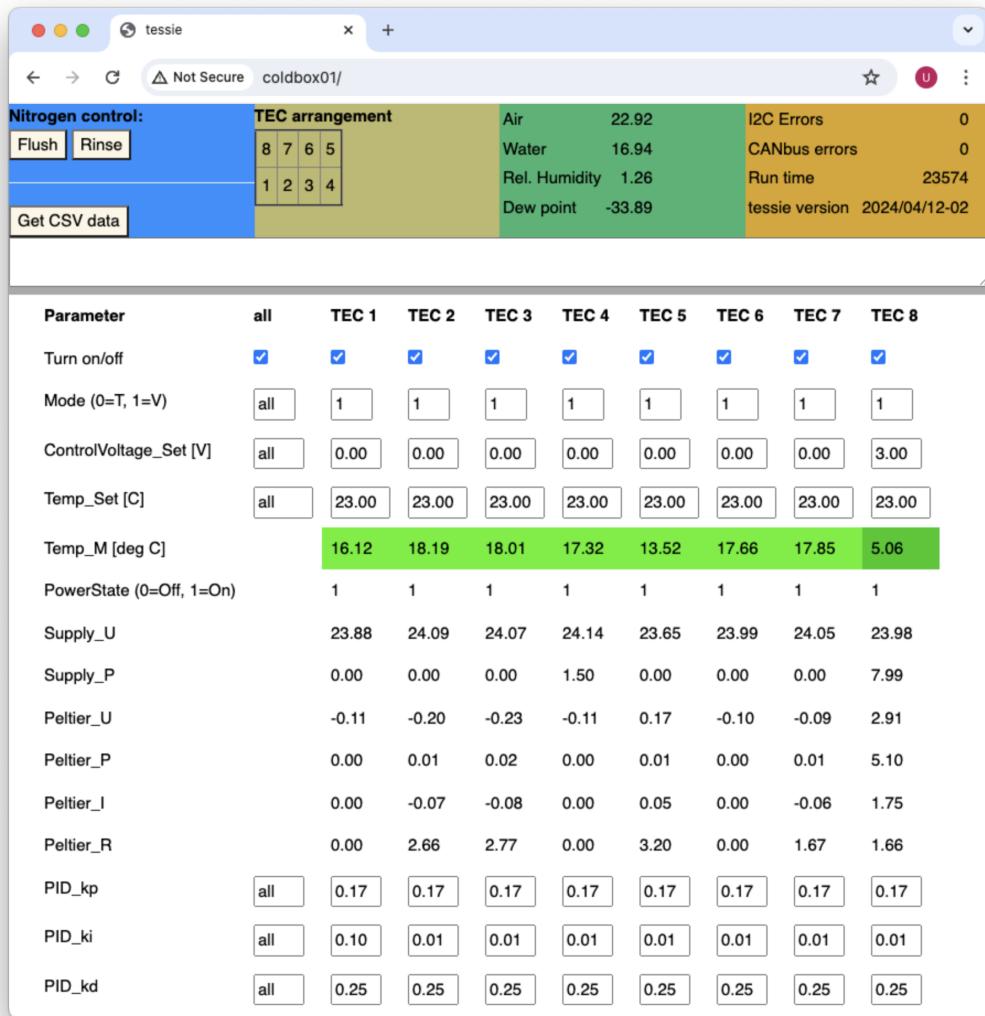


Figure 8: Web graphical interface to **tessie**. The top right brown-yellow box will turn red in case the connection to **tessieWeb** is interrupted.

4 Upgrading tessie or the TEC firmware

4.1 tessie upgrades

Note: It is strongly recommended to frequently update the tessie source code, and run an up-to-date version of the code!

Upgrading **tessie** is straightforward in a terminal. If you are using the HEAD of the master branch, do:

```
cd /home/pi/tessie
git pull
git checkout
cd src
qmake -o Makefile tessie.pro
make -j2
```

It can be argued that you should work with tagged versions of **tessie** to make sure that you are working with a tested, stable, and well-defined version of the software. Note that the tagged versions are described on the tessie github page [1]. You start with a tagged version using

```
cd /home/pi/tessie
git pull origin master
git fetch --tags
git checkout 2024/10/10-01
cd src
qmake -o Makefile tessie.pro
make -j2
```

Note that git will tell you that you are in a ‘detached HEAD’ state. Unless you intend to do code development, you can safely ignore it. If you want to do code development and commit your changes, read the rest of the warning message and do as told.

You can check which tags are available with

```
cd /home/pi/tessie
git --no-pager tag
```

If you want to go to the HEAD of the master branch (where all development takes place), do

```
cd /home/pi/tessie
git checkout master
```

To make the changes take effect, the minimal commands are:

```
sudo systemctl restart tessie
sudo systemctl restart tessieWeb
```

Alternatively, you can reboot the coldbox, either by turning it off/on (pressing the central power button) or in a terminal:

```
sudo shutdown -r now
```

In both cases, you can verify the update by comparing the version string of the GUI displayed on the Raspberry Pi’s touch screen and the web GUI (a reload of the page may be required).

4.2 TEC firmware upgrades

Upgrading the TEC firmware is done with the OpenBLT Bootloader [11], a very convenient tool for downloading micro-controller firmware over the CAN bus (plus other options, which are not relevant for this context). No additional cabling is required. A minimal version of this software is distributed with the `tessie` repository.

Start by compiling the bootloader's library and executable with the following commands:

```
cd /home/pi/tessie/tecFirmware/Source/LibOpenBLT
mkdir _build && cd _build
cmake ..
make

cd ../../BootCommander
mkdir _build && cd _build
cmake ..
make
```

Stop `tessie` before uploading the TEC firmware! So:

```
sudo systemctl stop tessie
```

After this you can upload, via the CANbus the firmware, contained in file `srec/tecware.srec`, of a single TEC with the following command:

```
cd /home/pi/tessie/tecFirmware
./BootCommander -s=xcp -t=xcp_can -d=can0 -b=125000 -tid=0x301 -rid=0x341 srec/tecware.srec
```

Note: This is the example command to upload TEC 1. For TEC i, both the `-tid=0x30i` and `-rid=0x30i` command line arguments should be modified accordingly.

To upload all TECs with the same firmware file, a (very) trivial shell script is provided:

```
cd /home/pi/tessie/tecFirmware
./flashAllTECs srec/tecware.srec
```

After this procedure, you can restart `tessie`:

```
sudo systemctl start tessie
```

5 Operational aspects

There are three methods to control the behavior of `tessie`:

- Graphical User Interface on the Raspberry Pi touchscreen
- Web Interface accessible with a web browser
- Text based interface based on MQTT

This section starts with a description of these three methods and afterwards discusses various aspects relevant to operations.

5.1 GUI - Raspberry Pi touchscreen interface to `tessie`

The GUI Raspberry Pi touchscreen interface is shown in Fig. 9.

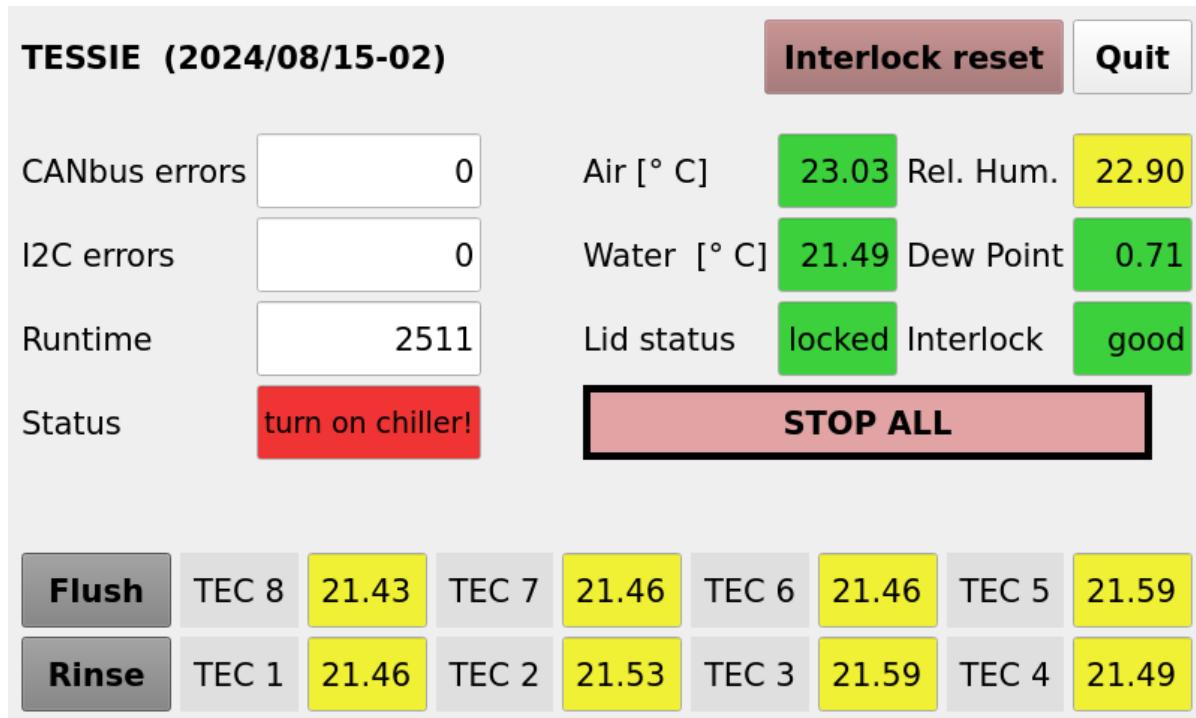


Figure 9: The GUI Raspberry Pi touchscreen interface to `tessie`

This GUI starts up on the Raspberry Pi touch screen after booting and provides a minimalist control surface to `tessie`. It allows for

- turning off and on the "Flush" and "Rinse" valves controlling the N2 flow,
- stopping all "dangerous" activities with the "STOP ALL" button that will turn off all TECs, turn on both "Flush" and "Rinse" valves, and disable the interlock (*i.e.*, switch it to LOW). It will make sure that the relative humidity in the box is minimal and that the power dissipated in the box is also minimal. This is the button you should hit if things go berserk.

- resetting the `tessie` interlock. This is required to put `tessie` into a normal state again after a condition occurred where the interlock was disabled. In addition to resetting `tessie`, you very likely will have to do something additional for your HV and LV powersupplies.
- quitting the `tessie` program.

All other controlling interactions with `tessie` should be initiated from the web interface, described in section 5.2.

The GUI displays the status of the system in three different blocks with multiple text displays with changing background colors.

System status The "CANbus errors" field accumulates the total number of CANbus errors over `tessie`'s running time. It will turn (shortly) red in case of a new CANbus error, *cf.* Fig. 10. If there is a persisting CANbus problem, it will stay red. The "I2C errors" field provides the same functionality for the I2C bus. "Runtime" show the `tessie` running time in seconds. The "Status" box tries to indicate the status of the box in normal terms.

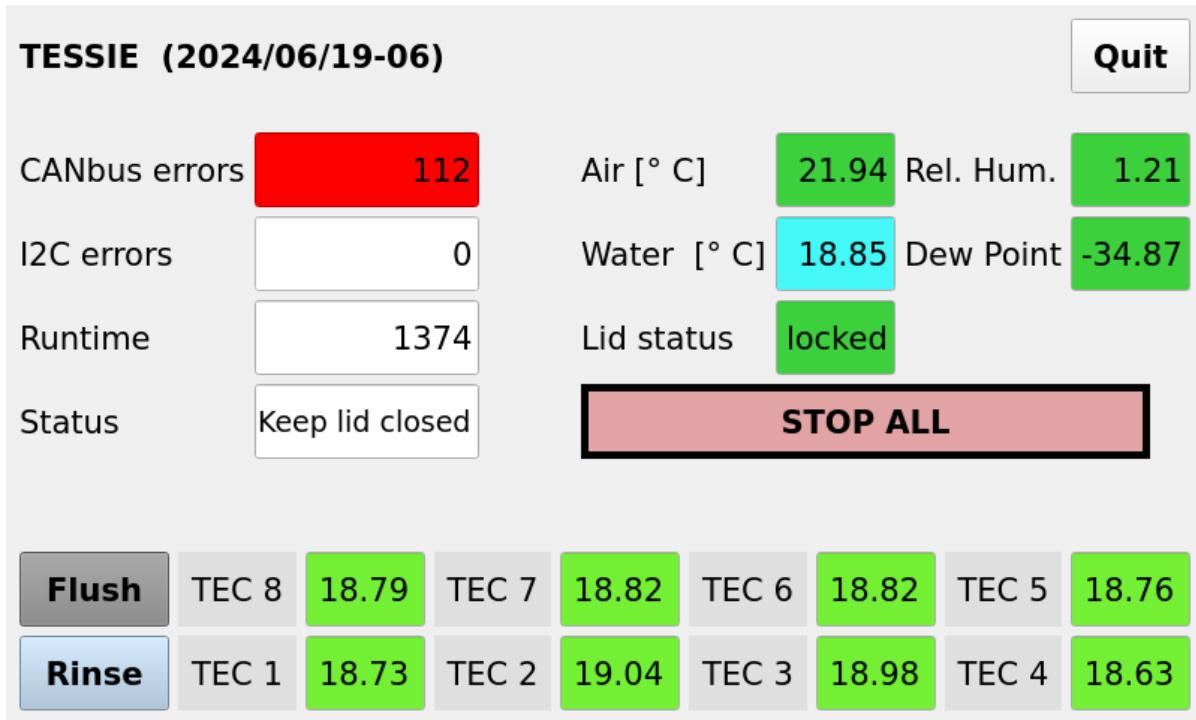


Figure 10: Illustration of the red background in case of many CANbus errors (this GUI screenshot refers to an older version of tessie, but the principle stays the same)

Environmental status The "Air" field indicates the air temperature as measured with the SHT85, located at one end of the PCB inside the coldbox. Its background changes with the air temperature between blue, green, yellow, and red. The "Water" field provides the same information for the cooling water temperature inside the coldbox, with the same color coding

as for the "Air" temperature field. The "Rel. Hum." field shows the air relative humidity in percent. It will turn green for values < 5%. The "Dew Point" shows the calculated dew point and is green if both the air temperature is at least 2°C warmer than the dew point. The "Lid status" indicates whether the lid is locked or not and changes color accordingly.

TEC status The labels with the TEC numbers change the color depending whether the TEC is powered or not, in a similar fashion as the valve buttons color scheme. The fields provide the temperature_{rec} [°C] of the PT-1000 on the TEC (*cf.* Fig. 5) with a changing background color scheme.

5.2 Web interface to tessie

FIXME

5.3 MQTT - direct text-based communication with tessie

Direct communication with **tessie** proceeds via two channels, either through the touchscreen GUI or through the MQTT protocol. The web GUI is not a *direct* communication channel, since it is only an interface to MQTT messaging.

The interface with MQTT proceeds through two threads, `ctrlTessie` and `monTessie`. The former is used to communicate commands while the latter display regular monitoring information broadcast by **tessie**.

To see the traffic on a thread, you "subscribe" to it with (*e.g.*)

```
mosquitto_sub -h coldbox03 -t "ctrlTessie"
```

To send commands over the `ctrlTessie` thread, you "publish" with (*e.g.*)

```
mosquitto_pub -h coldbox03 -t "ctrlTessie" -m "set valve0 on"
```

The **tessie** commands can be obtained with

```
mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "help"
```

This will result in

```
> =====
> hostname: coldbox01
> thread: ctrlTessie
> =====
>
> Note: [tec {0|x}] can be before or after {get|set|cmd XXX}, e.g.
>       cmd Power_On tec 7
>       tec 7 cmd Power_Off
>
> Note: tec numbering is from 1 .. 8. tec 0 refers to all TECs.
>
> cmd messages:
> -----
```

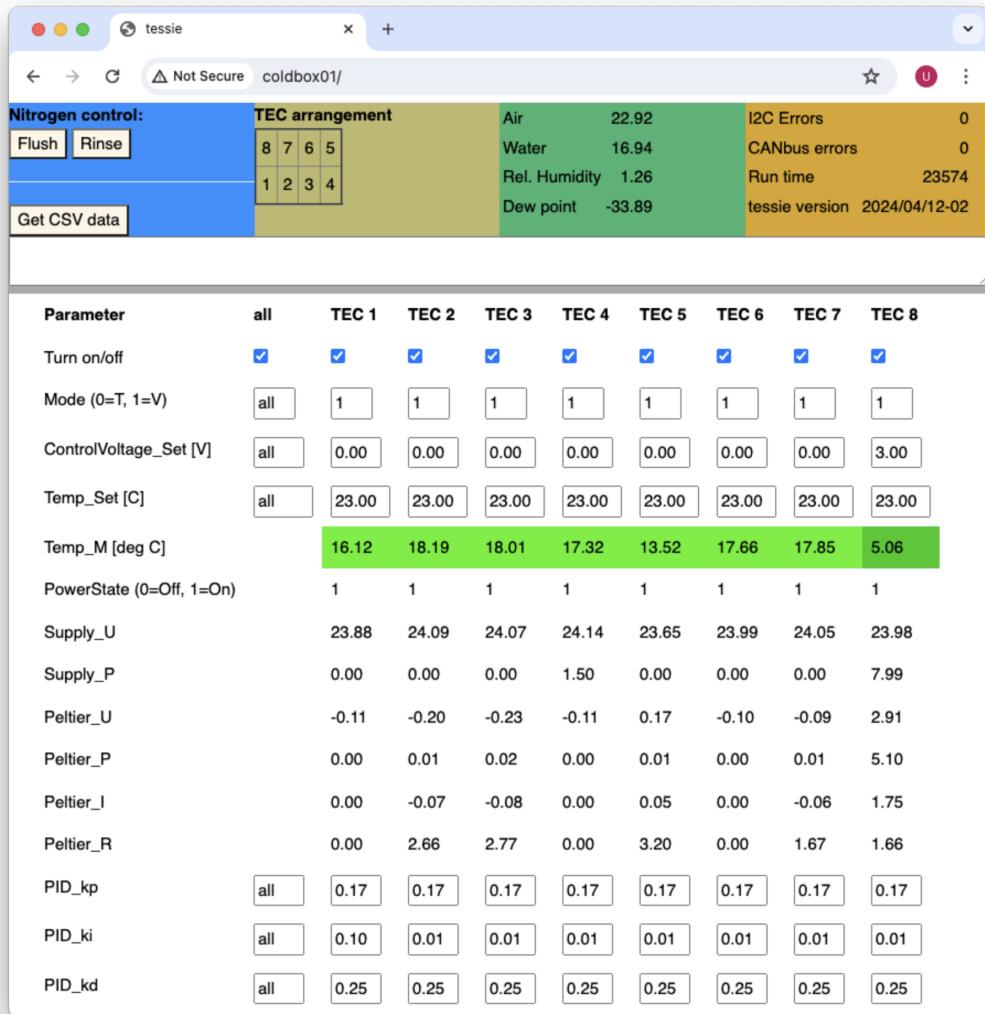


Figure 11: Web graphical interface to **tessie**.

```

> cmd valve0
> cmd valve1
> [tec {0|x}] cmd Power_On
> [tec {0|x}] cmd Power_Off
> [tec {0|x}] cmd ClearError
> [tec {0|x}] cmd GetSWVersion
> [tec {0|x}] cmd SaveVariables
> [tec {0|x}] cmd LoadVariables
> [tec {0|x}] cmd Reboot
>
> messages to write information:

```

```

> -----
> [tec {0|x}] set Mode {0,1}
> [tec {0|x}] set ControlVoltage_Set 1.1
> [tec {0|x}] set PID_kp 1.1
> [tec {0|x}] set PID_ki 1.1
> [tec {0|x}] set PID_kd 1.1
> [tec {0|x}] set Temp_Set 1.1
> [tec {0|x}] set PID_Max 1.1
> [tec {0|x}] set PID_Min 1.1
> set valve0 {on|off}
> set valve1 {on|off}
>
> messages to obtain information:
> -----
> get Temp
> get RH
> get DP
> get valve0
> get valve1
> get vprobe[1-8]
>
> [tec {0|x}] get Mode
> [tec {0|x}] get ControlVoltage_Set
> [tec {0|x}] get PID_kp
> [tec {0|x}] get PID_ki
> [tec {0|x}] get PID_kd
> [tec {0|x}] get Temp_Set
> [tec {0|x}] get PID_Max
> [tec {0|x}] get PID_Min
> [tec {0|x}] get Temp_W
> [tec {0|x}] get Temp_M
> [tec {0|x}] get Temp_Diff
> [tec {0|x}] get Peltier_U
> [tec {0|x}] get Peltier_I
> [tec {0|x}] get Peltier_R
> [tec {0|x}] get Peltier_P
> [tec {0|x}] get Supply_U
> [tec {0|x}] get Supply_I
> [tec {0|x}] get Supply_P
> [tec {0|x}] get PowerState
> [tec {0|x}] get Error
> [tec {0|x}] get Ref_U
> Tutorial for getting started:
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m " set valve0 on"
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "set valve1 on"
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "set ControlVoltage_Set 4.5"

```

```
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "cmd Power_On"
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "cmd Power_Off"
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "set ControlVoltage_Set 0.0"
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "set valve0 off"
> mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "set valve1 off"
```

You should carefully read the two Notes. Issuing a command like, for instance, `cmd tec 7 Power_off` will not work, has not been promised to work, and there are no intentions to change this behavior.

5.4 Safe operations limits

To ensure the safety of the coldbox equipment, the TEC controllers and the FRAS relais require a “heartbeat” command from `tessie` at periodic intervals (3 seconds for both; `tessie` sends the command every second). If that expected “heartbeat” signal is not registered, these components stop operating (*e.g.*, the TECs are shut off and no longer provide cooling for the modules).

In addition, `tessie` continuously monitors environmental parameters to ensure a safe operation of the coldbox in case of operator error. Table 3 provides a summary of the safe operation parameters. An alarm is raised if `tessie` registers a violation, *cf.* Section 5.8. If

Table 3: Safe operations parameters monitored by `tessie`. In this table “module temperature” indicates the PT1000 temperature reading mounted on the Peltier module.

Parameter	min [deg]	max [deg]
box air temperature	n/a	40
water temperature	n/a	30
module temperature	n/a	30
difference between box air temperature and dew point	2	n/a
difference between module temperature and dew point	2	n/a

any temperature (box air, water, modules, copper block) exceeds 40°C, `tessie` will turn off all TECs and trigger the interlock procedure. In addition, it will ensure maximum N2 flow by opening the `Rinse` and `Flush` valves.

5.5 First steps

To start operations on (*e.g.*) `coldbox03`, the following instructions might be helpful (in case you need them).

Turn on Load the module(s) into slot(s). Close the lid and ensure that it is properly locked.

- Turn on the chiller and make sure it is not in standby mode.
- On any computer connected to the same network as your `coldbox03` point a browser to <http://coldbox03>. All manual interactions described below are done on this web GUI.

- Reduce the relative humidity inside the coldbox by opening the N2 valves, initially both **Flush** and **Rinse**. Once the dew point is sufficiently low, you may turn off the **Flush** flow. Note: it is a matter of your hardware (screw) settings whether **Rinse** is sufficient to keep the relative humidity low.
- Set the voltage on the TECs to be operated (a good starting value is 3 V) by entering the value into the boxed field.
- Turn on the TEC by clicking the corresponding checkbox.
- Observe how the module temperature drops.

It is now safe to power (LV/HV) the module and run electrical tests.

Turn off Before turning off the coldbox, turn off the power (LV/HV) on the modules in the coldbox and then proceed according to the following list

- Turn off the TECs by clicking the checkbox.
- Turn on the N2 flow **Flush** to faster warm up the coldbox and keep the relative humidity low.
- Wait until the temperature inside the box is close to the room temperature.
- Turn off the N2 flow, both **Flush** and **Rinse**.

It is now safe to open the lid and remove the module(s).

5.6 Direct readout of probe card

In principle, the probe card [7] readout should be handled by higher-level software. However, it is also possible to do a direct readout of the probe card with MQTT. In one terminal subscribe to the **ctrlTessie** thread with

```
mosquitto_sub
-h coldbox01 -t "ctrlTessie"
```

In a second terminal, assuming that you have a probe card at slot 8, issue the read command

```
mosquitto_pub -h coldbox01 -t "ctrlTessie" -m "get vprobe8"
```

You will receive, in the first terminal (the one where you have subscribed to the **ctrlTessie** thread), two lines with the following format:

```
get vprobe8
2024/04/12 11:34:40 -0.0004 0.07 -0.10 0.10 0.10 5.05e-05 0.10 5.06e-05 -0.10 0.001
```

The first line repeats the command given in the second terminal and then the result of that readback is provided. The interpretation of the numbers is as follows

```
date time vin voffs vdda0 vddd0 vdda1 vddd1 vdda2 vddd2 vdda3 vddd3
```

corresponding to the input voltage, offset, and the read digital and analog voltages of the 4 chips on the module.

FIXME: if you have better information that could be added here, please inform me.

5.7 Traffic Lights

Three lights are used for a visual display of the operations status of the coldbox, cf. Table 4.

Table 4: “Traffic light” display of the `tessie` status.

Color	State	Meaning
Green	on	Safe to open the box, all environmental parameters in safe range
Green	off	Not safe to open the box
Yellow	on	At least one TEC turned on (e.g., during a test)
Yellow	blinking	No TEC turned on, but not safe to open the box.
Yellow	off	No TEC turned on
Red	on	Alarm active (see section 5.8)
Red	off	No alarm active

5.8 Alarm channels

`tessie` raises an alarm in case operational issues require human intervention. The alarm is raised as soon as `tessie` observes a measurement violating the safe operation region. The alarms are propagated via various means

- the alarm condition is broadcast to the `ctrlTessie` and `monTessie` MQTT channels
- an alarming sound is played through an attached loudspeaker inside the coldbox. All connected web GUIs will also play the sound in case the user has given the browser (tab) permission to play audio.
- the “traffic” light display of the coldbox displays a constant red light

In addition to the alarms raised, `tessie` also issues warnings for I2C and CAN bus errors. These warnings are accumulated as counters in the GUIs (both the web GUI and the GUI running on the coldbox touch screen). In addition, a warning sound is played.

5.9 Modes for cooling the TECs

There are two modes for cooling the TECs, *cf.* Figs. 7 and 8. The setting `Mode = 0` enables the TEC controller’s PID control algorithm to set the TEC temperature to the value specified in the `Temp_Set` value, while the setting `Mode = 1` applies a fixed voltage `ControlVoltage_Set` to the TECs (in the range $0 < \text{ControlVoltage_Set} < 11$ V). Table 5 provides an approximate translation between the setting of `ControlVoltage_Set` and the temperature measured on the PT1000 attached to the TEC, *cf.* Fig. 5.

5.10 Temperatures on the TEC and module

The temperature measured with an NTC on the chip of a digital module has been studied and is compared to the temperatures on the module TEC. The accuracy of this NTC is of the order a few degrees, as estimated from the difference between the temperatures measured in chips 14 and 15 as shown in Fig. 12.

Table 5: Approximate translation between `ControlVoltage_Set` and PT1000 temperature `Temperature_M`, with the temperature measured on a powered HDI. Note: this translation depends on the cooling liquid temperature!

<code>ControlVoltage_Set</code> [V]	<code>Temperature_M</code> [°C]	<code>HDI temperature</code> [°C]
1	20	35–38
2	15	30–35
3	7	20–25
4	0	15–20
5	-4	12–17
FIXME	add	more

The NTC readout was obtained with the Ph2-ACF software (version v4-15) using the command

```
CMSITminiDAQ -f CMSIT_RD53B.xml -c ntc
```

It should be noted that the TEC temperature differs by about -15°C from the chip temperature. This may be similar to the situation in the experiment, where the chips will also not be at the same temperature as the cooling.

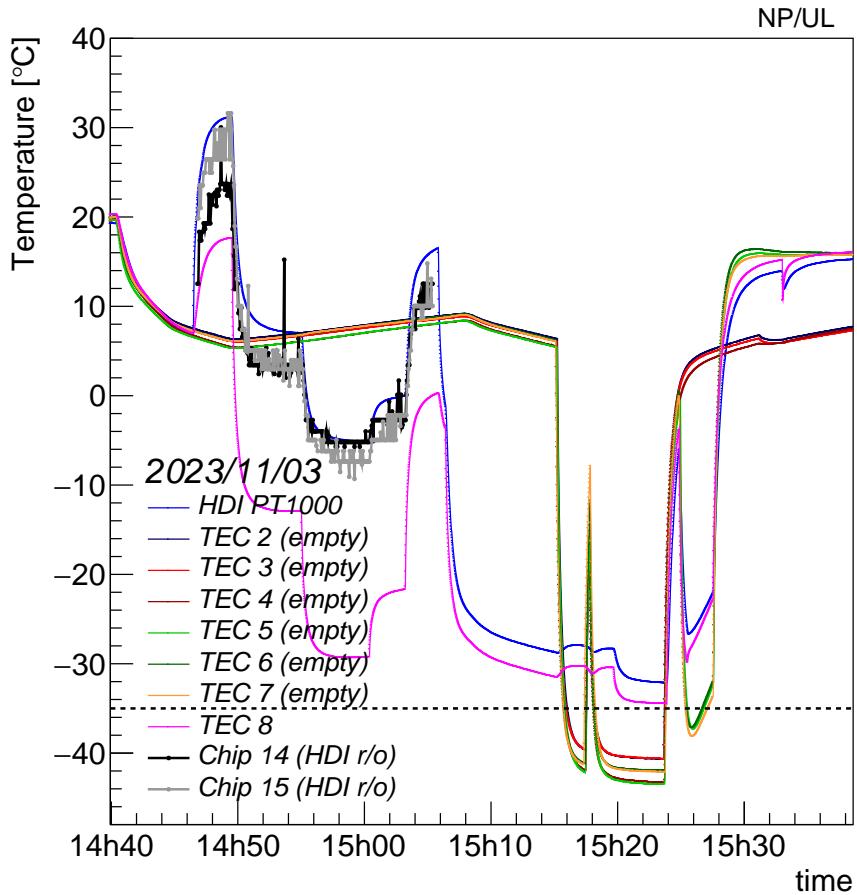


Figure 12: Temperature measurements with a digital module. Note that there is a difference of about 15°C between the chip temperature and the module TEC temperature with a powered module (there would be no HDI temperature readout without powering). The short-dashed line is at $T = -35^{\circ}\text{C}$, to guide the eye.

6 Frequently asked questions

This sections aims to provide help for errors and issues that may be encountered with the coldbox and/or `tessie`, during operation or installation.

6.1 Operations

Many of the issues discussed here are indicated by error, warning, and/or alarm messages being broadcast to the MQTT channels `ctrlTessie` and `monTessie`, the red light of the traffic light turning on, sound messages being played, and other highlighting background colors in the `tessie` GUI on the coldbox touchscreen (cf. Fig. 9).

6.1.1 Do's and don'ts

What are the most important aspects when operating the coldbox?

Answer: The Do's are

- Turn on the chiller
- Ensure the chiller is running
- Ensure that a loudspeaker is connected (play the test sound via the GUI button or see below in subsection 6.2.4)
- Ensure that the browser tab is unmuted

Do not

- operate the coldbox without the chiller running
- be impatient with the web UI or the GUI. Other web UI instances might be connected and need to be synchronized.
- ignore error messages or alarms
- disconnect the loudspeaker or lower its volume
- mute the browser tab with the web UI

6.1.2 tessie does not start

It can happen that after a reboot `tessie` cannot display the GUI on the Raspberry Pi touchscreen. This happens possibly because of a race conditions after a fresh Raspberry Pi powerup. The quick-n-dirty fix: Simply reboot the Raspberry Pi, either through the power button or with `sudo shutdown -r now` on the command line. That should work.

The better approach is to add the following text to the file `/lib/systemd/system/tessie.service` to have the following content:

```

[Unit]
Description=tessie
After=network.target

[Service]
Type=idle
User=pi
Group=staff
Environment="XAUTHORITY=/home/pi/.Xauthority"
Environment="DISPLAY=:0"
WorkingDirectory=/home/pi/tessie/src
ExecStartPre=/home/pi/tessie/resetCAN.sh
ExecStart=/home/pi/tessie/src/tessie -f
StandardOutput=inherit
StandardError=inherit
Restart=on-failure
RestartSec=2s

[Install]
WantedBy=graphical.target

```

Note the two "Restart" lines.

6.1.3 An alarm goes off if I plug in a module and close the lid

A possible reason for this condition could be that you turned on the chiller, opened the lid to connect a module, closed the lid and then did *not* turn on the N2 flow. The chiller water will cool the Peltier element to whatever temperature you set the water temperature to and this temperature may well be below the dew point (especially in Summer, when the ambient air humidity is high). This will trigger the alarm `module ... too close to dew point ...`

Solution: Turn of N2 flow (either flush or rinse or both).

6.1.4 Alarm module temperature exceeds SAFETY_MAXTEMPM (single module)

The reason for this condition is likely that you powered a module without turning on the corresponding TEC.

Solution: Turn on the corresponding TEC cooling or power-off the module.

6.1.5 Alarm module temperature exceeds SAFETY_MAXTEMPM (single module)

The reason for this condition is likely that you turned on one TEC, and then off again, without turning on the chiller (or there is no flow in the water). This can warm the entire side (1–4 or 5–8) of the coldbox and, because of variations between the different TEC temperature sensing, a single module can go above the limit before the others do so. It can take a while to get into this state. Note: If, from previous interactions with the coldbox, the water is still below 20°C, `tessie` will allow turning on the chiller despite it not running.

Solution: Turn on the chiller.

6.1.6 Alarm module temperature exceeds SAFETY_MAXTEMPM (many modules)

The reason for this condition is likely that you turned on (some or all) TEC without turning on the chiller. It takes a few minutes to get into this state. Note: If, from previous interactions with the coldbox, the water is still below 20°C, `tessie` will allow turning on the chiller despite it not running.

Solution: Turn on the chiller.

6.1.7 The CANbus shows many errors

The reason for this problem is likely some electrical condition affecting the CANbus due to operator manipulations or to missing components (lid sensor) or to bridged components (*e.g.* replacing the lid sensor with a resistor).

Solution: Restart `tessie` either by power-cycling the coldbox with the central power button or by logging in from a remote computer and doing

```
ssh coldbox
sudo systemctl restart tessie
```

6.1.8 Persistent issue with a single TEC

The “issue” could be CAN bus errors (showing up as, *e.g.* temperature readings of -999°C) or other examples. This could be due to a blown fuse on the TEC.

Solution: Replace the fuse on the TEC, *cf.* Fig. 3.

6.1.9 Where is the printout/logfile/CSV file from `tessie`?

For a better understanding of possible issues with `tessie` sometimes you need access to the printout, especially if you have looked into the code. *Solution:* You can see the printout with `journalctl`.

```
journalctl -u tessie -b
journalctl --since "24 hour ago" -u tessie
```

The option `-b` yields all messages since the last boot, the second example restricts this to the specified time period.

There are logfiles in the running directory of `tessie`, normally in `/home/pi/tessie/src`. The running instance of `tessie` is writing to `tessie.txt` and all previous logfiles are kept with timestamps attached (*e.g.*, `tessie.txt.20241004.10:22:25.366`)

In addition to the logfiles, a CSV file (comma-separated values), `tessie.csv`, is filled by `tessie`. The values in that file correspond to

```
date,T-air,RH,DP,T-water,powerState[8],Vset[8],Tset[8],T-module[8]
```

where `date` is the date and timestamp of the following values, `T-air`, `RH`, `DP` are the temperature, relative humidity, and dew point of the air inside the coldbox, respectively. `T-water` provides the cooling liquid temperature. The remainder of the line come in groups of 8 values for the 8 TECs: `powerState` indicates whether the TECs are turned on (enabled), `Vset` provides the `ControlVoltage_Set` in Volts, `Tset` shows the programmed `Temp_Set` in degrees Centigrade, and finally `T-module` provides the module temperatures.

6.1.10 The N2 flow valves are not working, but no CANbus errors appear

One possibility is that a connector on the FRAS has a shaky contact, *cf.* Fig. 13. This can be indicated by no LED on the FRAS being lighted.



Figure 13: Photo of the FRAS. The connectors for the sockets (A1/A2/D-/D+) labeled with “Power Supply” and “CAN Bus”) supplied by the manufacturer with this device, are prone to shaky contacts and should be secured by some (improvised) means.

Solution: Open the box (take off the lid for that purpose) and ensure a proper contact of the connector, *e.g.*, by tying it down with a cable tie.

6.2 Installation

6.2.1 The touchscreen is white

This is an indication that the flatband cable connector is not properly inserted into its socket. The fact that initially the touchscreen showed a colorful pattern is no contra-indication, that simply indicates that it has power.

Solution: Unplug the flatband cable and insert once again.

6.2.2 The touchscreen gradually turns white and stays white.

This can happen during the first boot after inserting a fresh SD card and normally changes after repeated reboots (done automatically by the system). If it persists, then most likely you used an image that is not the recommended version.

Solution: Burn a new iso image using the following [img](#). This issue was posted to stackexchange ([here](#)), but it remains unresolved.

6.2.3 Server certificate verification ...

... error messages when trying to run [apt-get](#). This can happen if you have not set the correct time and date.

Solution: Set the date and time using the following command (replacing the example values with the correct value)

```
sudo date -s "Wed Apr 17 2024 10:00:00"
```

6.2.4 How to test the USB loudspeaker and tessie audio alarms

The easiest (and still reasonably safe) way is to make sure that the coldbox is empty (no module loaded!) set one TEC to Mode = 1 and ControlVoltage_Set to 3 V. (This should be done via the web interface.) This will turn on the TEC, which will lower the (Peltier module) temperature below the dew point. Once the temperature is closer than 2°C to the dew point (cf. Table 3), the alarm will go off. You will see this visually on the GUI (TEC temperature field indicator flashing red) and you should hear the alarm. At this point, you can turn off the TEC and all should be well again. Note: You should hear the alarm from two sources! (1) the USB loudspeaker in the coldbox should emit the alarm, and (2) the web browser should sound the alarm on the computer. If one of these two sources is not present, fix it.

Another possibility is to hit the "Test sound" button on the GUI. This button is not available on the web UI. Currently, it tests only the coldbox loudspeaker and will not sound the alarms in a web browser.

Note: This will play the entire mp3 file for a duration of about 50 seconds. Hitting the button again will not stop the playing, but will prolong the playing.

References

- [1] Urs Langenegger, “tessie”. <https://github.com/ursl/tessie>.
- [2] Steve Corrigan, “Introduction to the Controller Area Network (CAN)”.
<https://www.ti.com/lit/an/sloa101b/sloa101b.pdf>.
- [3] Jonathan Valdez, Jared Becker, “Understanding the I2C Bus”.
<https://www.ti.com/lit/an/slva704/slva704.pdf>.
- [4] MQTT.org, “MQTT: The Standard for IoT Messaging”. <https://mqtt.org/>.
- [5] Sensirion - The sensor company, “Datasheet SHT85 - Humidity and Temperature Sensor”. https://sensirion.com/media/documents/4B40CEF3/61642381/Sensirion_Humidity_Sensors_SHT85_Datasheet.pdf.
- [6] Noah Piqué, “Coldbox Development at PSI”. CMS Inner Tracker Modules Meeting, November 30, 2023 (<https://indico.cern.ch/event/1349094/>).
- [7] Beat Meier, et al., “Voltage probecard”.
<https://psi-lab.docs.cern.ch/coldbox/vprobe/>
<https://gitlab.cern.ch/psi/moduleprobe/>.
- [8] Wilke Technology, “CAN Output FRAS4 4x Relais Out”. https://wilke.de/fileadmin/templates/daten/DATA_Sheet_DV-CANFRAS4-01_EN.pdf.
- [9] Noah Piqué, “Coldbox assembly manual”.
<https://psi-lab.docs.cern.ch/coldbox/assembly/>.
- [10] Raspberry Pi OS, “Raspberry Pi Imager”. <https://www.raspberrypi.com/software/>.
- [11] FEASER, “OpenBLT Bootloader”.
<https://www.feaser.com/openblt/doku.php?id=homepage>.