Summary V3

Preview

- Ferrari to support IIT to design and simulate a ventilator for sub-intensive patient use in emergency: low cost is one of main goals.
- Simulink model have been created from scratck which includes:
    1. Three matematical model of human lungs (stiff, avgm soft) → *Respirtory Mechanics Derived From Signals In The Ventilator Circuit*
    2. Air/Oxigen mixing device (to reach O2 target %) and pressure regulator to allow inlet valve to operate in controlled pressure
    3. Main flow line with controlled valves, safety check valves, quick disconnect, pipes (capacitive and resistive).
- Main outcome from the model is to validate hardware layout in terms of component selection and operating pressure level across the entire system.

Main results

- Inlet valve
    - **Camozzi AP** valve are currently below target having low maximum flowrate at its most permeable setting (low preload spring) and its maximum operating pressure (1 bar)
    - **Camozzi CP** valve operating at 750mbar of inlet pressure will match all usage requirement having a full open flowrate >80lpm while we estimated to use as maximum 60-65lpm as maximum requirement.
- Outlet valve **CFB-D24M-R1** is the target valve to evaquate lungs air flow without affect exhalation dynamics. For the prototype is ok to run with **CFB-D22G-W1**
- Permeability scan to asses robustness of the system does not highlight any criticallities.
- Pressure changes using helmet instead of mask (+8L) lead to a 100cc of tidal volume lost. Increasing V1 command current by 4-5% is possible to recover entirely lungs tidal volume matching mask-like pressure dynamics.
- Inlet mixing volume is not needed if the mixer is inherently pressure compensated (as most of the ones on the markets).
- **CO2 rebreathing** will be not an issue using **mask with <250ml of volume**. For both bigger mask and helmet, valve duty has to be increased significantly to reduce CO2 concentration below 2% limits. **Flow-by is the most effective strategy on this purpose**.
- FMEA results
    - If water bottle vent valve is fitted no issue in evacuating exceeding air flowrate. Maximun calculated mouth pressure will be **safely equal to the vent cranking pressure**.
    - Without water vent valve, mechanical check valve needs to be permeable to not increase consistently patient's mouth pressure. Considering 100 mbar of max mouth pressure allowed, check valve permeability target will be **of 110 lpm at 160mbar**.

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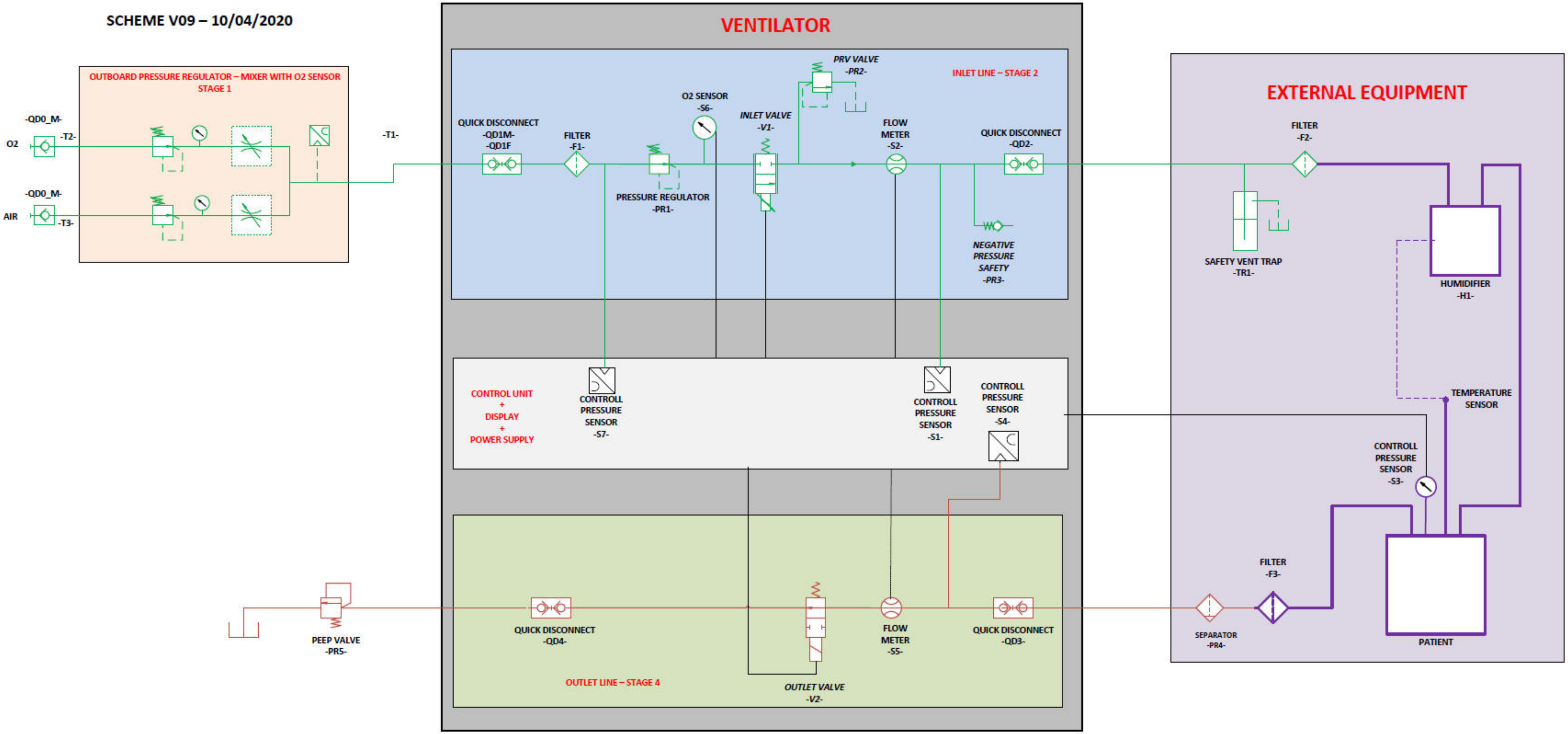
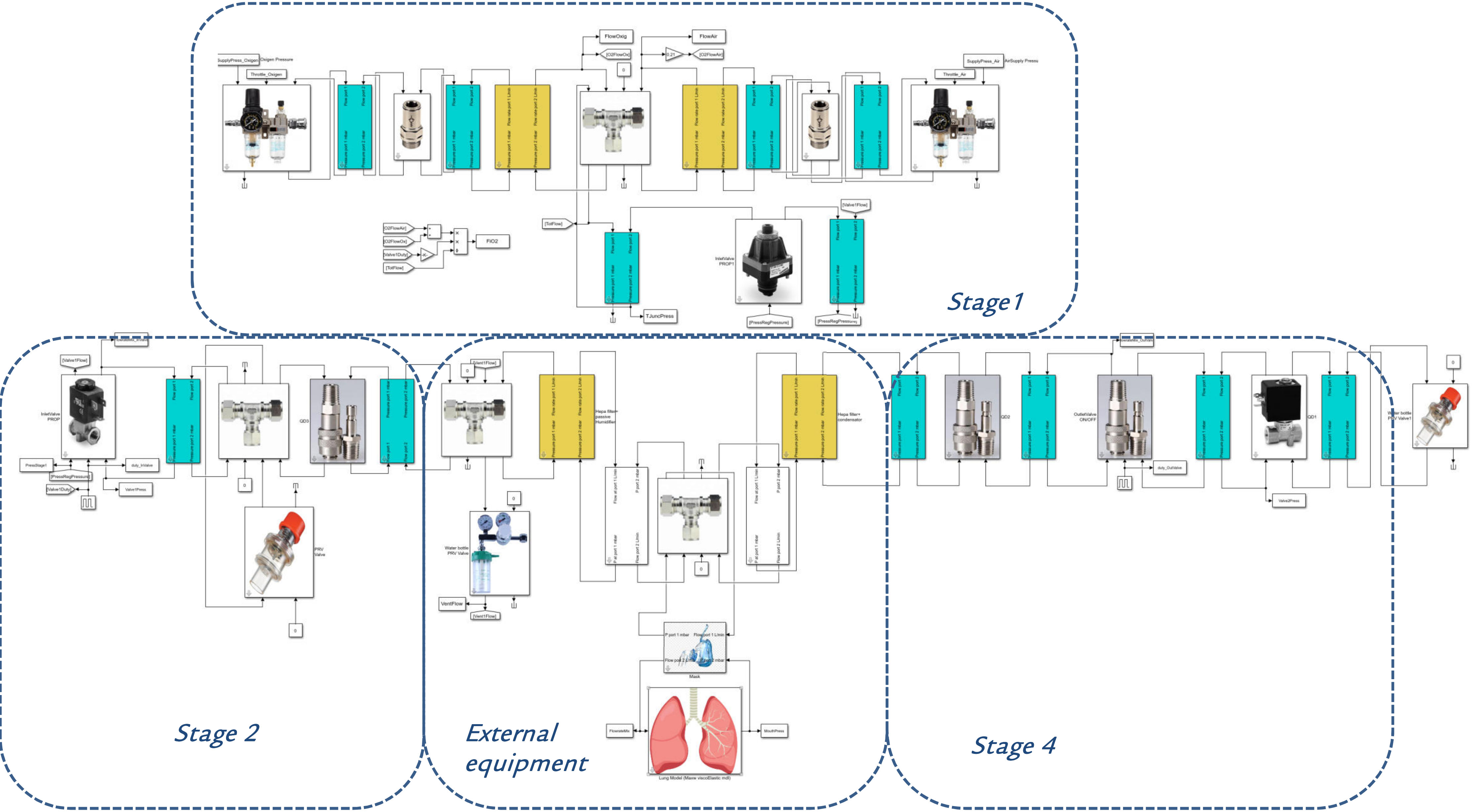
Schematic layout of the BSF system



Simulink model scheme



Lung compliance characteristics

On «*Respiratory mechanics derived from signals in the ventilator circuit*» are reported different human lung with three different compliance (tidal volume is identical for all three).

We replicated the three flowrate curves into the model to compare derived pressure curves with the lung model originally used (blu line) and comes out that **it's pretty similar to an high compliance lung**.

Assuming that the spread in the picture is real (waiting for medical confirmation) simulation need to consider in any condition **the worst possibile characteristic** to define a reasonable worst case.

RESPIRATORY MECHANICS DERIVED FROM SIGNALS IN THE VENTILATOR CIRCUIT

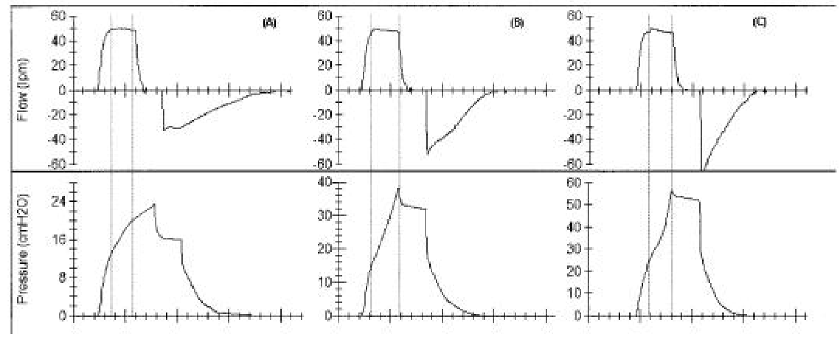
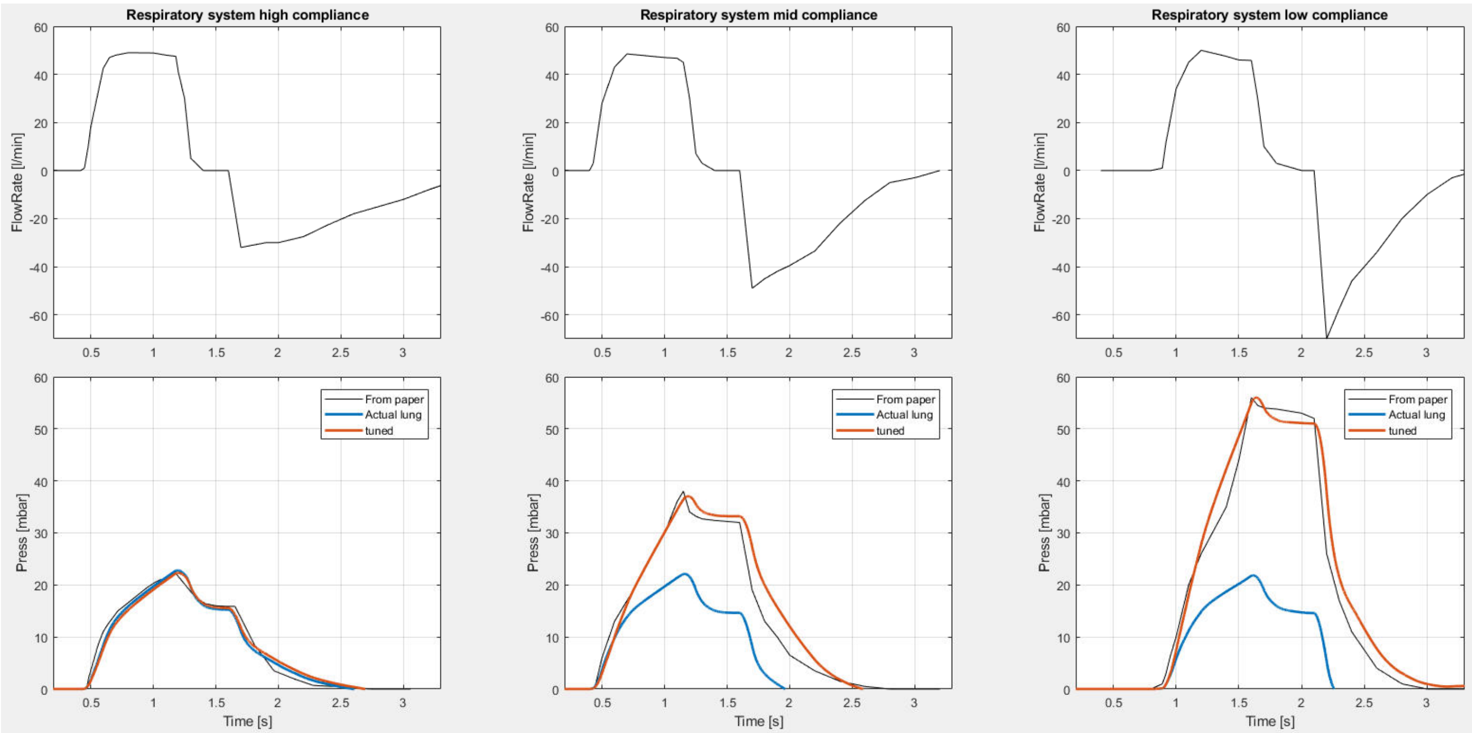


Fig. 2. Time-course of static airway pressure, flow, and volume during volume-controlled ventilation. From panel A to panel C, respiratory system compliance decreases. The constant-flow phase is defined by the dotted lines, which show the elastic load on the pressure curve. As peak inspiratory pressure increases, the morphology of the curve changes, turning from concave to linear to convex.

High compliance lungs (line the old modeled) **will be worse for V1 valve** dimensioning because it clearly request more flowrates for a given mouth pressure, while a **low compliance one results worse for V2** valve because it releases higher flow peak when the valve starts opening.

Lung parameter have been manually tuned to match all three pressure curves to allow always to simulate the desided lung characteristic each case.

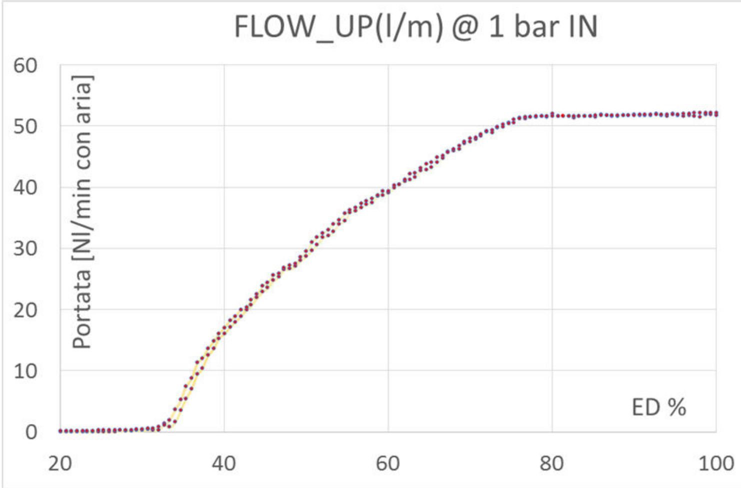


PR1 & V1: AP valve permeability target

Target is to reduce as much as possible the operating pressure of PR1 due to safety reson. Camozzi's max AP valve (*taglia 22 ugello 2.4mm*) cannot guaranteed target flowrate even at 1.5 bar of inlet pressure. **Reducing valve interal spring preload** is possible to increase valve premeability reaching the value in the plots below. Desired valve must satify target air flow rate with high compliance lung characteristic (*25-30 mbar mouth pressure*) at 50% of it's FS current to have margin to include components scatter and to reach strong dynamics in pressure control.

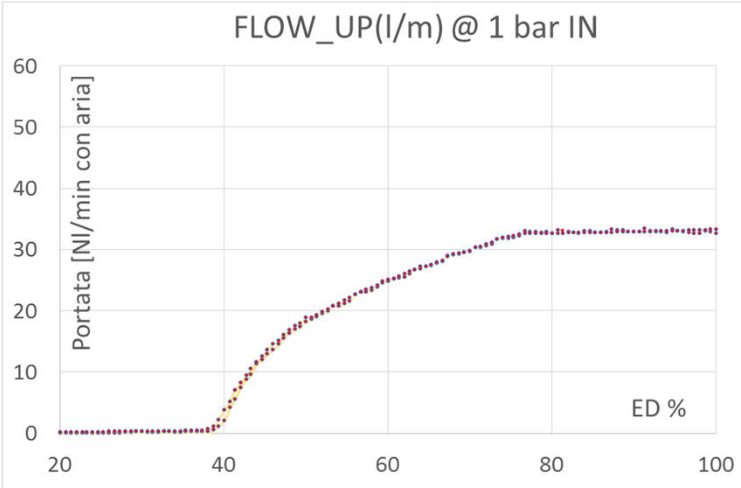
PR1 @1000 mbar

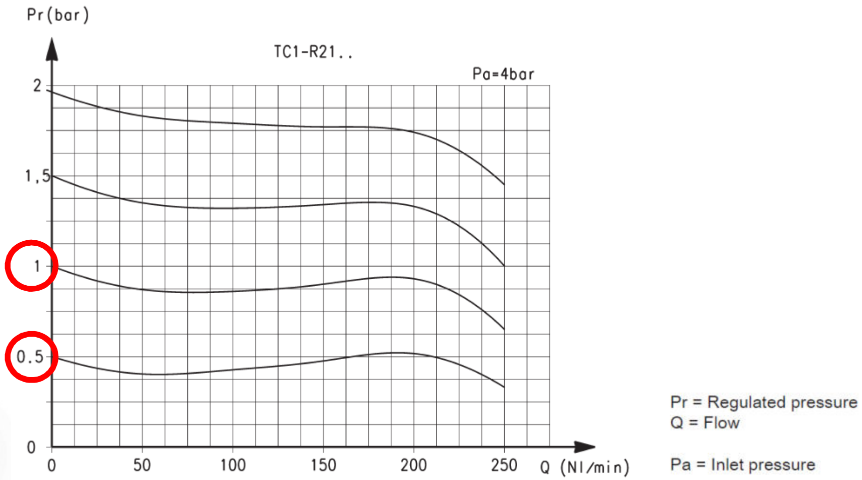
- minimum preload spirng leads to results on top right figure. Usual working point will be at 50% of FS current but flowrate strongly saturate from 78% onward due to the small orficieht at the exit of the valve. **This valve will be tight to guarantee sufficient margin** for air deliver in high pressure dynamics and CO2 reduction using helmet s.



PR1 @500 mbar

- Curve from Camozzi (bottom right figure) shows too low flowrate in all operating condition.





PR1 & V1: CP valve

CP valve, due to the presence of an ugello of 4.4 mm, is inherently more permeabile. CP flushing test have been performed in Camozzi on 10/04/2020 and the results have been used to feed the model.

750 mbar of PR1 pressure will be ideal case due to the reduced maximum flow delivered at 100% FS current and normal condition at 46% of FS current. 1 bar will provide too high flowrate in fully open condition while 500 mbar of pressure start to become tight for max delivered flowrate.

PR1 @1000 mbar

- minimum %FS current to satify target pressure is **45%. Too high flow rate** level if running @100%FS current (>100 lpm), such high flow could be challenging to be evacuated in check valves

PR1 @750 mbar

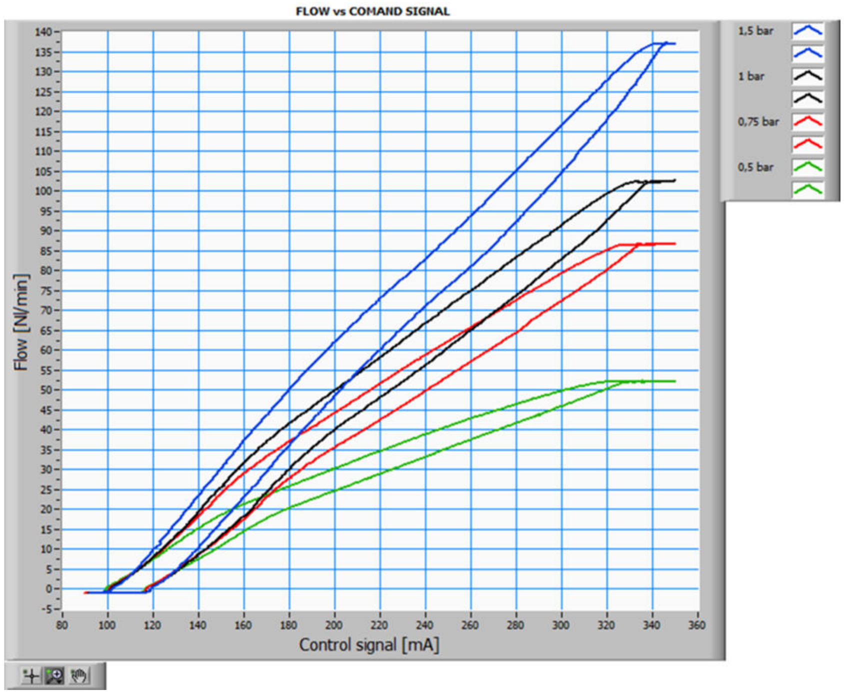
- minimum %FS current to satify target pressure will be pretty similar to 1bar pressure, **46%, due to the simililarity of the two curves at the begnning** Flow rate @100%FS current become less dangerous (around 88lpm) running this pressure level.

PR1 @500 mbar

- minimum %FS current to satify target pressure is **51%.** Flow rate @100%FS will be slightly higher tha 50lpm which could becaome limiting factor to follow desired dynamics on pressure target.

Diametro nominale 4.4 mm

Q = portata (Nl/min)
I = corrente (A)
P1 = pressione in carico (bar)
P2 = 0 [pressione a flusso libero] (bar)
FS = fondo scala



Feedbck from a doctor will clarify max valve requirement.

CP valve flowrate test

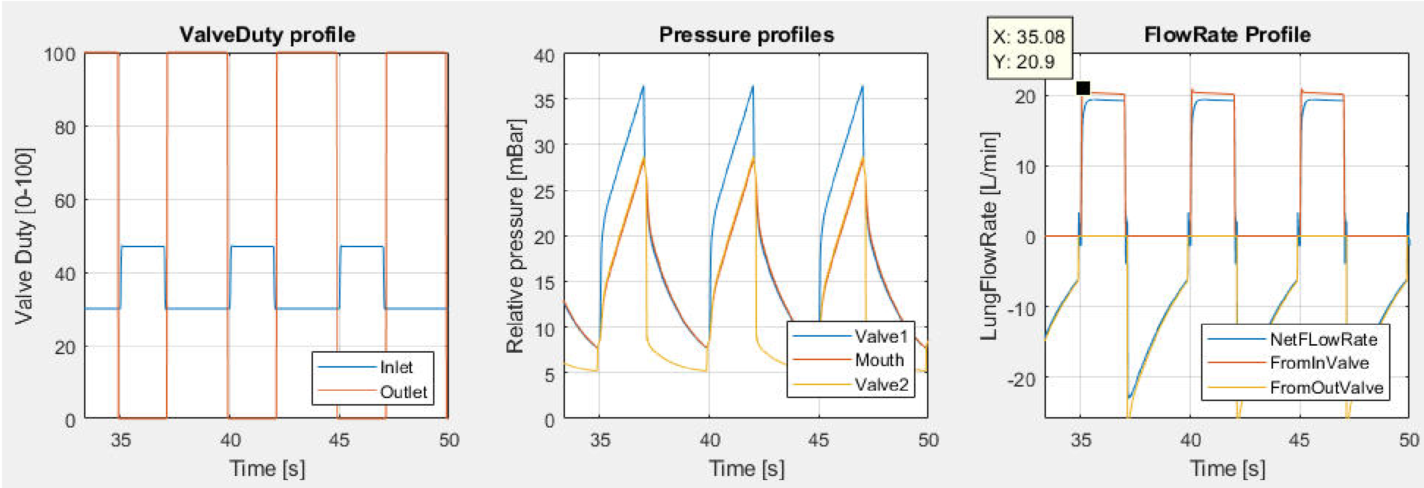
Below two simulation results using CP valve at 750 mbar inlet pressure considering an high compliance lung characteristics.

Top graph refers to a 12 cyc/min breathing frequency and in this case the required flowrate peak will be around 21lpm. Bottom graph refers to higher frequency and here the **flowrate request increase significantly up to 38 lpm**.

Considering 30-40% margin in valve flowrate and considering that an excess of flowrate will be needed in order to shape the pressure curve as desired (more like step) this confirms that maximum valve flowrate must be above the region of 60/65lpm.

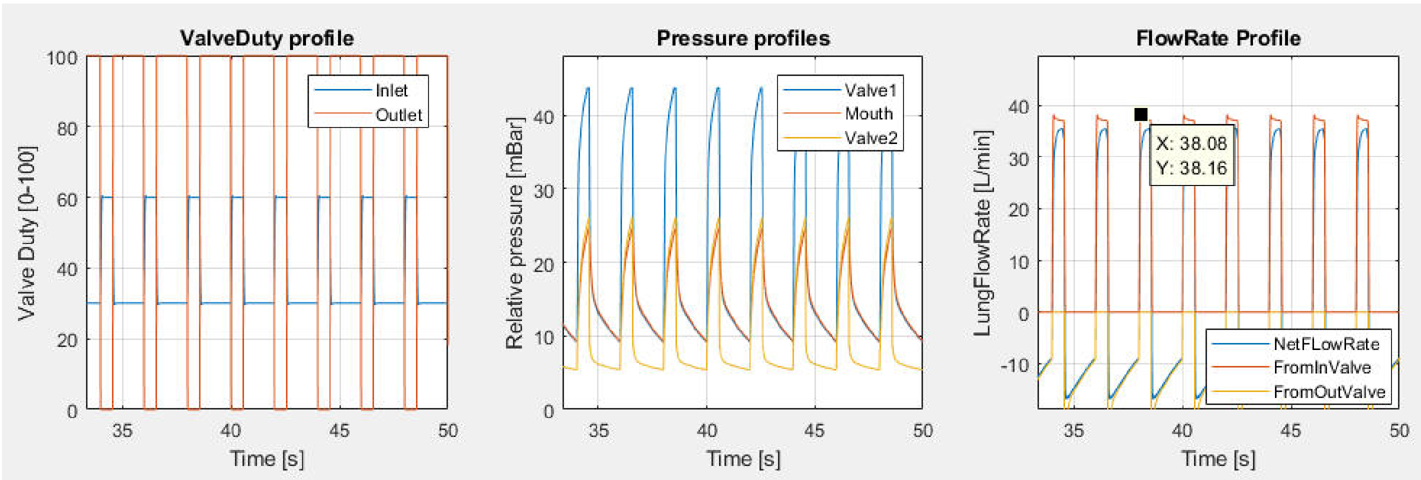
Normal breath freq

12 cycl/min



High breath freq

30 cycl/min



V2 valve permeability threshold

Below a scan of outlet valve permeability using Camozzi physical components, considering the worst case of **stiffest lung characteristic**.

Simulation have been performed with two breath frequency and in both scenarios the **system is saturated using a permeability of Kv 1.7.** The effect of a less permeable valve (the one selected for prototype - Kv 0.6 - cod. CFB-D22G-W1) is not really critical because it affect just slightly the pressure profile on 12 cycl/min but will increase by 1mbar final pressure curve in 30 cyc/min scenario.

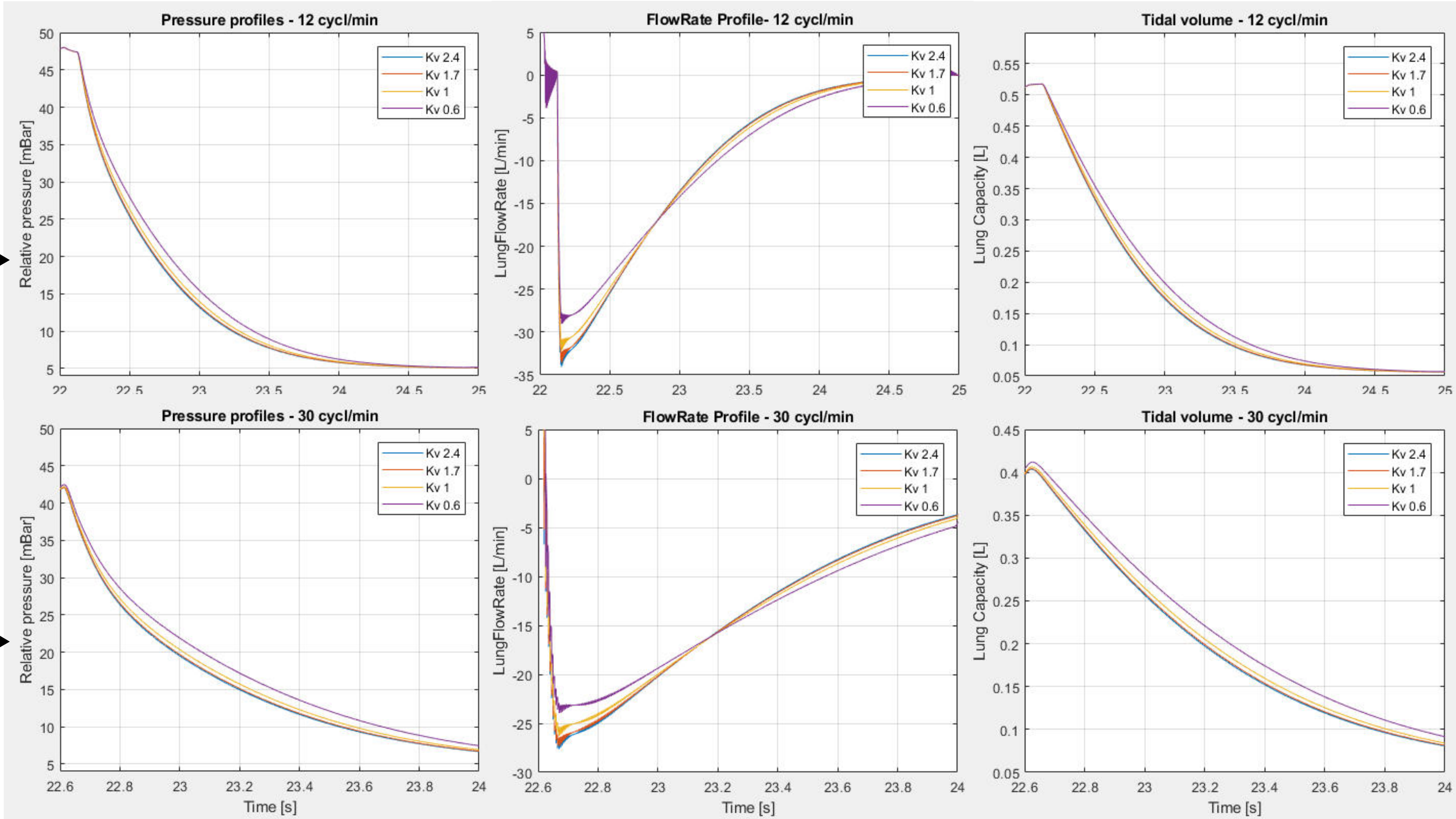
Since a Kv of 2.4 is available **(cod. CFB-D24M-R1) we would suggest to use that one** repeating that the less permeable one will be ok for initial productive batch.

Normal breath freq

12 cycl/min

High breath freq

30 cycl/min



Flow line pressure drop and permeability scan

Table shows system main source of pressure drop: main one comes from filters and flowmeter. For the device which are not in the line (like vent and check valve) the value reported are a target of permeability to satify requirements (see FMEA section). In line permeability scan have been performed to asses the robustness of the results on this parameters.

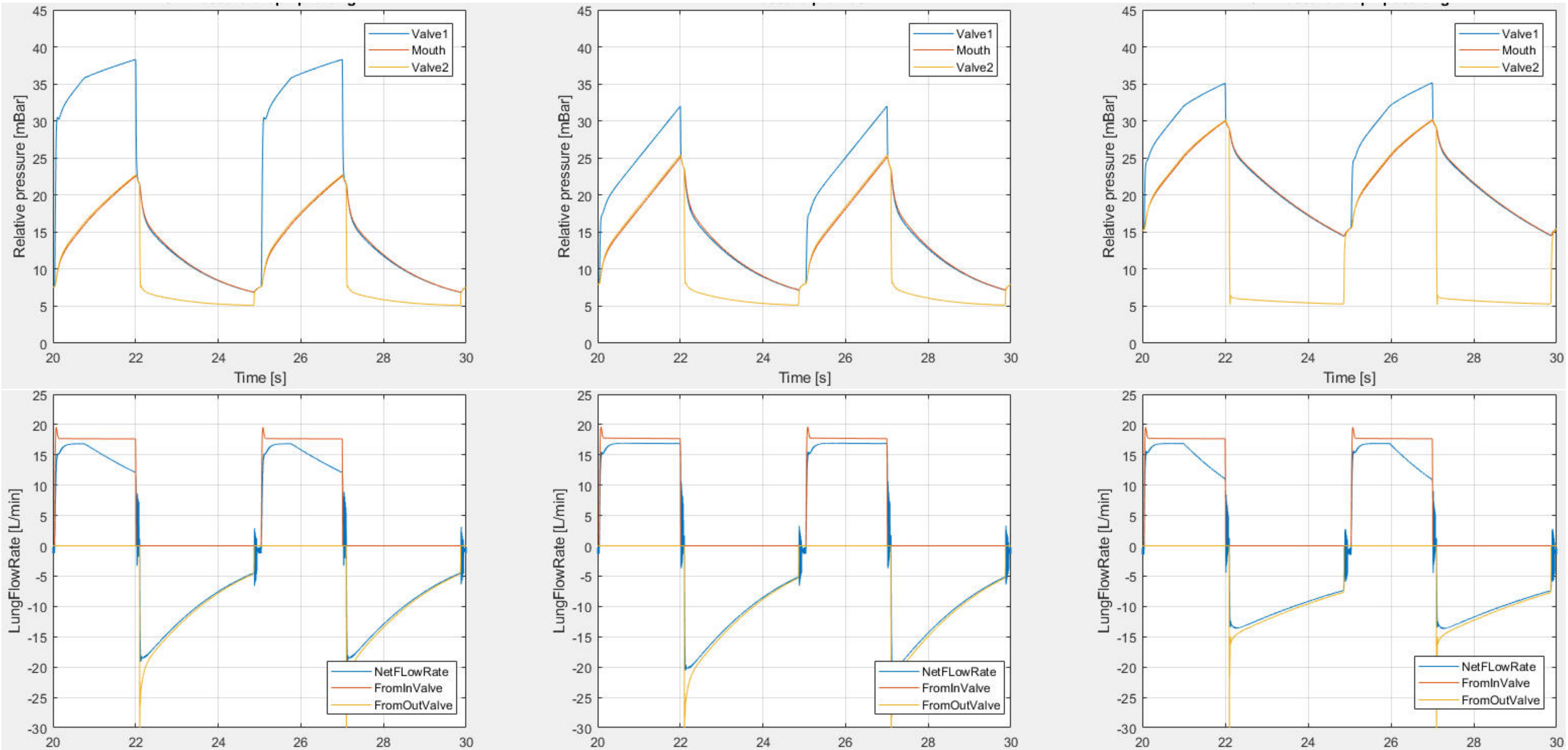
- **Increasing 3x dP upstream** of the lung does not affect much mouth pressure (as expected), control is expected to compensate this effect completely. Water must be added to prevent air flwo on vent valve.
- **Increasing 3x dP downstream** of lung will increases mouth pressure curves. The effect will be the same of fit less permeable peep valve.

Name	INLine / Deriv	Note	Flow [Lpm]	dP [mbar]
Pipe	inline	22mm Din, 1.5mt long, corrugated	20	0.04
QD	inline	Conical conenction	20	0.1
Flowmeter	inline	Honeywell datasheet	20	2.44
Filter	inline	"used" HEPA	20	5
Humidifier	inline		20	0.2
PEEP	inline	averaged from customers	20	1.76
Check valve	deriv	cranking press 80mbar	106	80
Vent valve	deriv	30-50 mbar of water press	10	5

3x dP upstream lung — dP from table — 3x dP downstream lung

FlowRate

Pressure

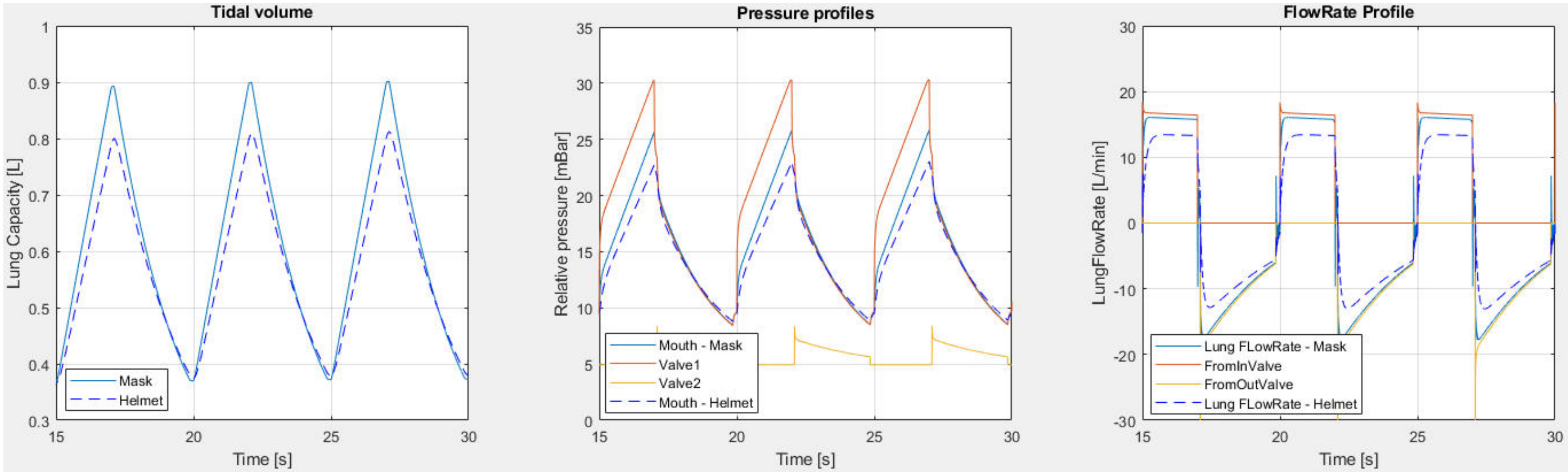


Effect on pressure dynamics helmet VS mask

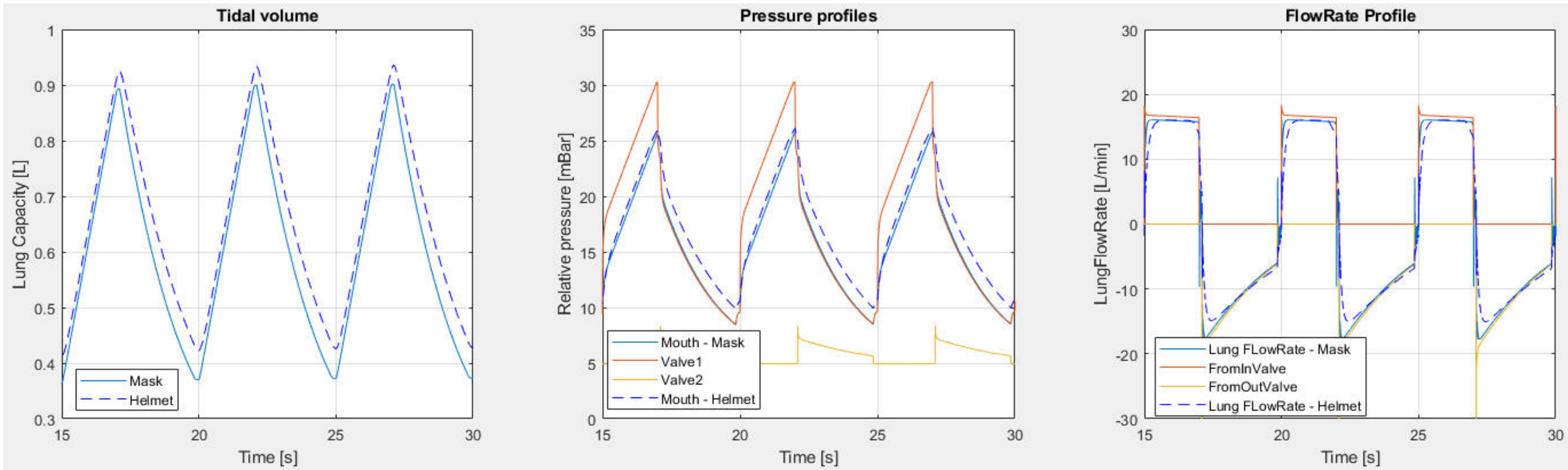
A volume of 0.5L for mask and **8L for helmet** have been considered for this calculation; please note that no air leakage have been modeled in helmet case (although probably there is). Dotted line in following graph represent case with helmet.

With almost +8L volume before patient muth pressure dynamics changes a significantly.

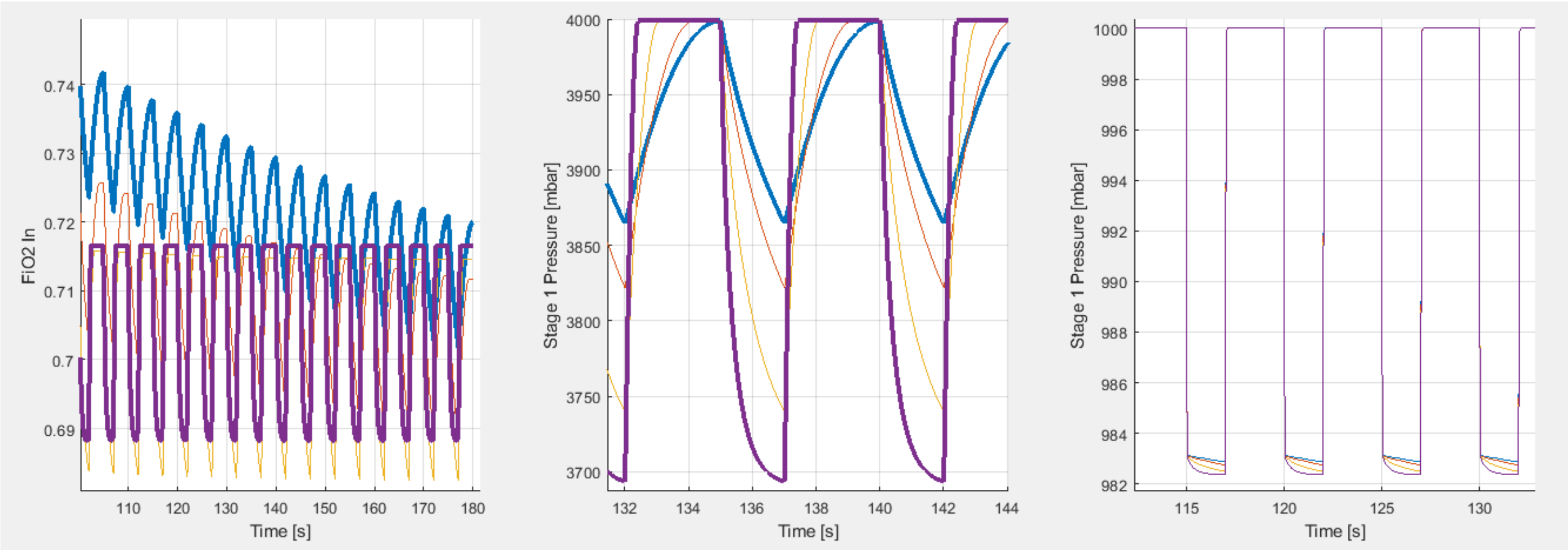
100cc of tidal volume will be lost due to the reduction of either 3 mbar mouth pressure and 4l/min of lungs inflation flowrate.



Increasing V1 command current by 4-5% is possible to recover entirely lungs tidal volume matching mask-like pressure dynamics.
Expiration phase is driven by lungs dynamics and cannot be replicated using helmet.



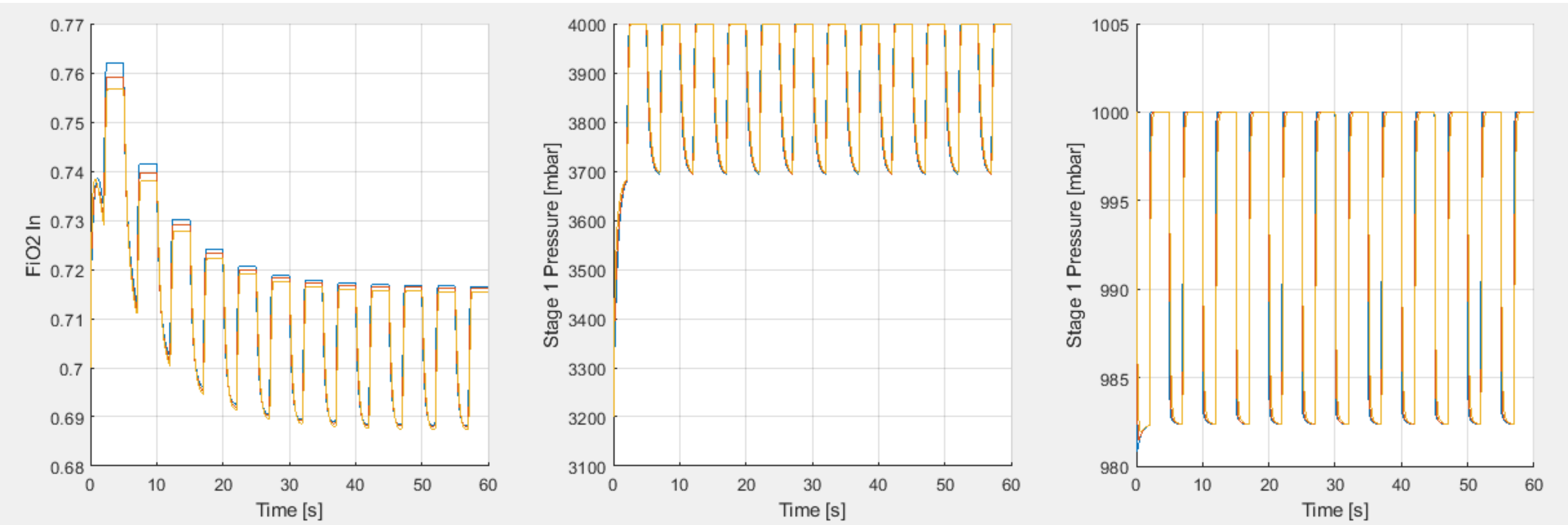
System volumes stage1 and 2 (4 bar O2 supply, 4 bar Air supply)



The curves are plotted for different gas volumes of stage 1 (upper graphs) and 2 (lower graph):

0.1 L
1 L
3 L
5L

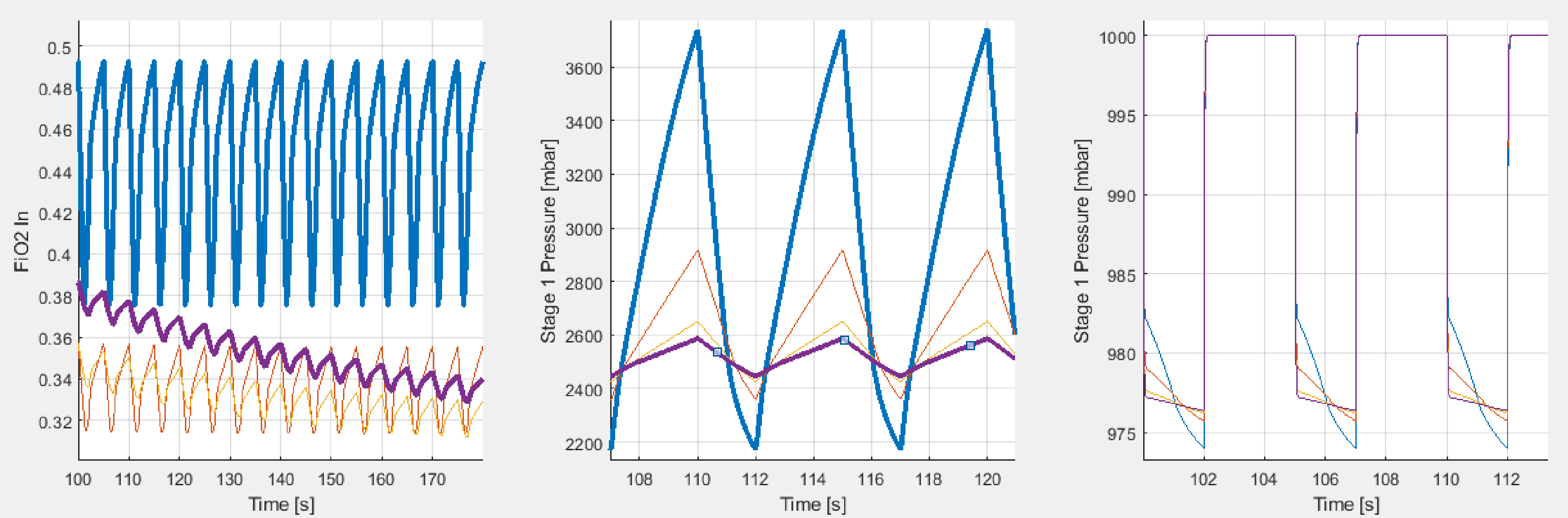
Influence of stage 1 volume on FiO2, stage 1 P and stage 2 P.



The effect of the stage 2 volume is negligible as expected from the ideal behaviour of the pressure regulator. Increasing the stage 1 volume stabilize pressure, but even in the worst case the dynamics are quite slow and should be handled by the pressure regulator.
The FiO2 is stable (within a 3% band)

Influence of stage 2 volume on FiO2, stage 1 P and stage 2 P.

System volumes stage1 and 2 (2.5 bar O2 supply, 4 bar Air supply)



The curves are plotted for different gas volumes of stage 1 (upper graphs) and 2 (lower graph):

0.1 L
1 L
3 L
5L

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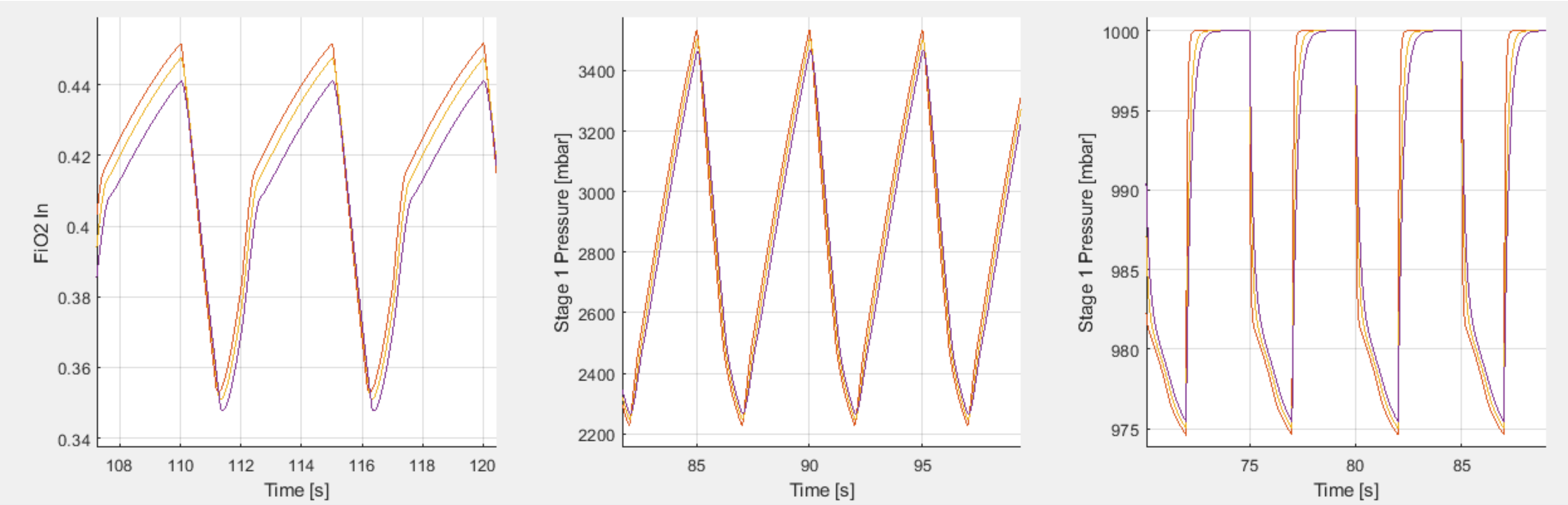


The effect of the stage 2 volume is negligible, while the stage 1 volume has quite a big effect and at least 3L are needed to stabilize pressures and FiO2.

Influence of stage 2 volume on FiO2, stage 1 P and stage 2 P.

Commercial mixer scheme

Sechrist Air / Oxygen Gas Mixers - Model 3600 & Model 3601

Provides for precise mixing of air and oxygen for many clinical applications. Models 3600 and 3601 are high flow mixers designed for general applications. 3601 utilizes a wall mount configuration and 3600 provides for pole mounting.

•Accuracy*: +/- 3% • Flow at 60% FIO2 and 50 psig •Supply Pressure: 100 LPM
•Bleed Flow: 8 - 10 LPM @ 16 LPM Flow Rate • FIO2 Range: 0.21 +0.01 to 1.0-0.1
•Gas Supply Range: 50 psig +/- 20 psig

Model 3600

Standard Accessories:
Water Trap Assembly

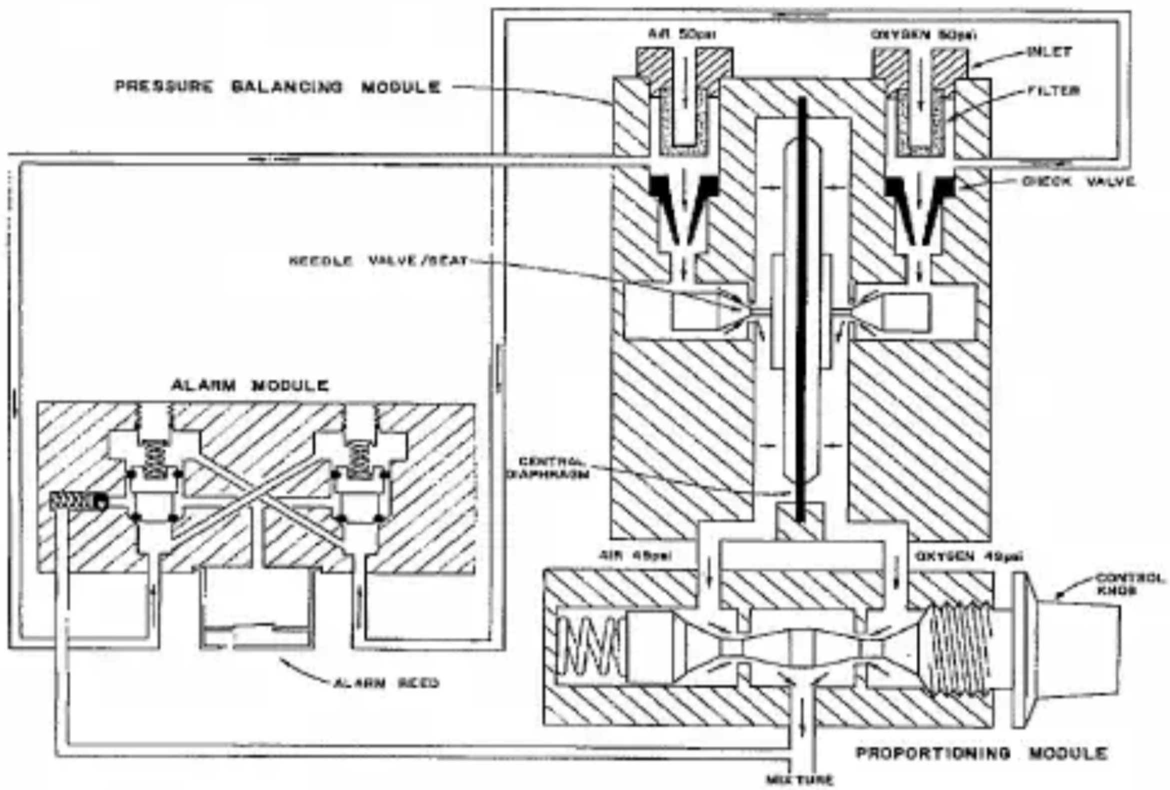
Optional Accessories:
14ft air hose/14ft oxygen hose,
both with DISS fittings

Model 3601

Standard Accessories:
Water Trap Assembly

Optional Accessories:
14ft air hose/14ft oxygen hose,
both with DISS fittings

Commercial mixers are designed to compensate for the different pressures in the feeing lines, **and in this way there is no need of a mixing volume.**



CO2 rebreathing

CO_2 concentration in air	Symptoms and effects of inhaling CO_2
1% - 1.5%	Effetto leggero sul metabolismo dopo l'esposizione di diverse ore
3%	Il gas è debolmente narcotico a questo livello, dando luogo a respirazione più profonda, ridotta capacità uditiva, accoppiato con mal di testa, un aumento della pressione sanguigna e della frequenza cardiaca
4 - 5%	La stimolazione del centro respiratorio si verifica con conseguente respirazione più profonda e più rapida. I segni di intossicazione diventeranno più evidenti dopo l'esposizione di 30 minuti
5 - 10%	La respirazione diventa più faticoso con mal di testa e perdita dei sensi
10 - 100 %	Quando l'anidride carbonica concentrazione aumenta superiori al 10%, perdita di coscienza si verifica in meno di un minuto e se non si interviene pronta, ulteriore esposizione a questi alti livelli finirà per provocare la morte

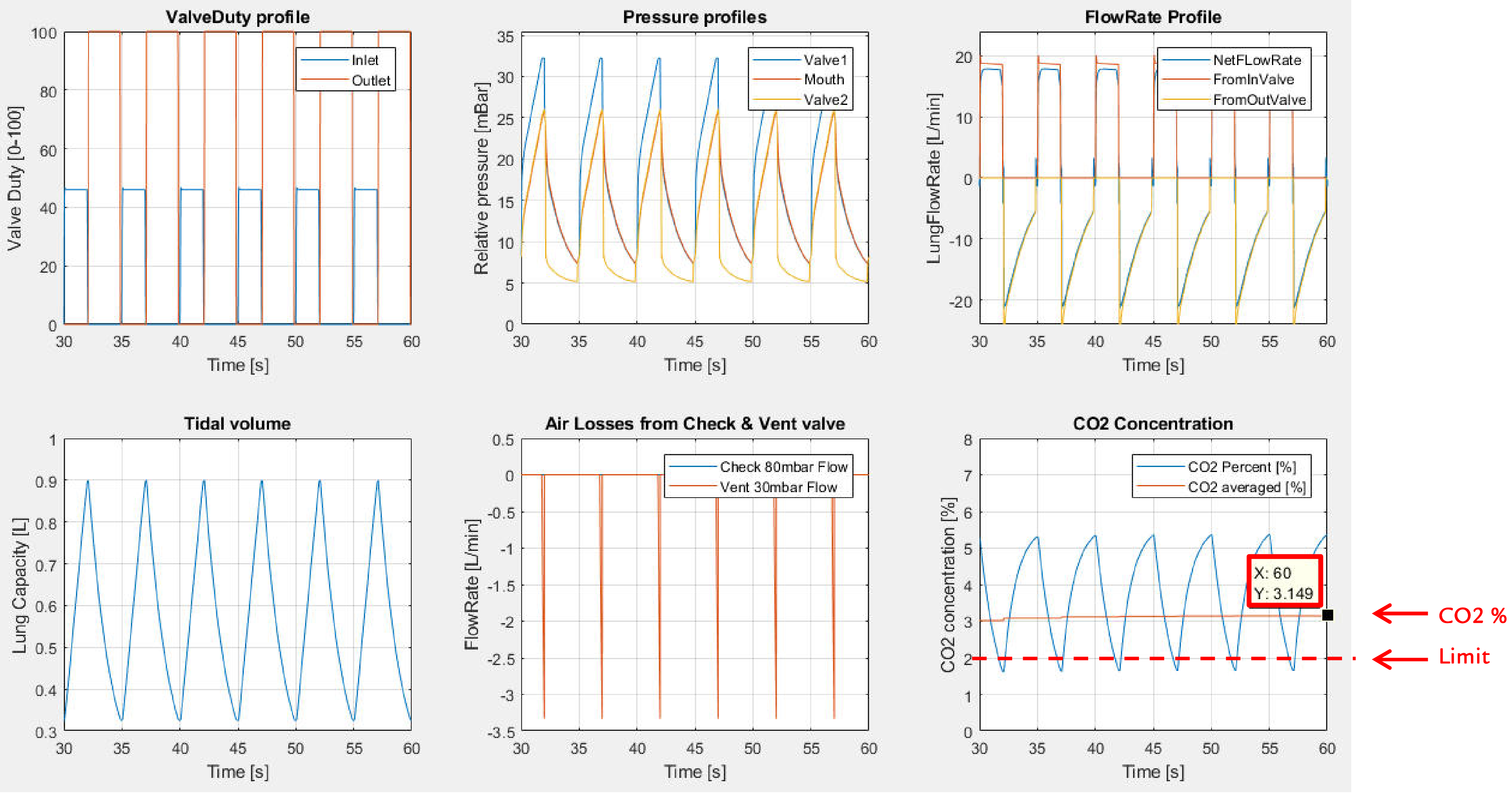
In normal condition the CO2 rebreathing could be a serious issue (see table above, a medical advice is need on this item). If we have to keep it under control, the ventilator operation has to be changed.

CO2 rebreathing Mask - BSL

From medical feedback, max CO2 concentration must not exceed 2%. With **mask smaller than 250ml** CO2 stabilize at lower value so no need of any dedicated strategies to reduce CO2 concentration.

Over this volume mask can accumulate critical value of CO2, for example having **500 ml as worst case** scenario, concentration tend to stabilize in half a minute at **3.1%**. Different options will be simulated in order to study the best solution to lower CO2:

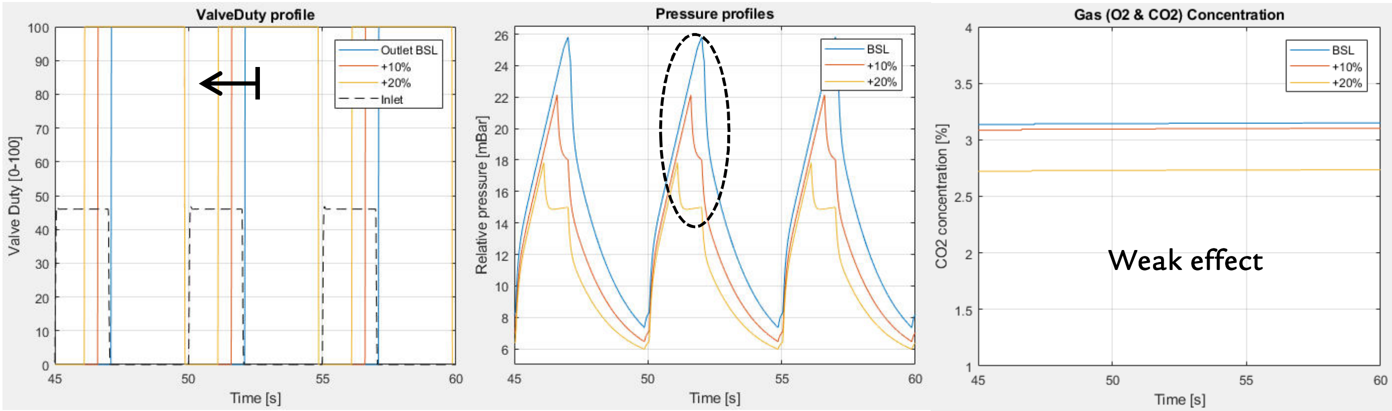
1. Valves overlap on inhalation phase
2. Valves overlap on on exhalation phase
3. Valve1 minimum flow



CO2 rebreathing Mask - Strategies

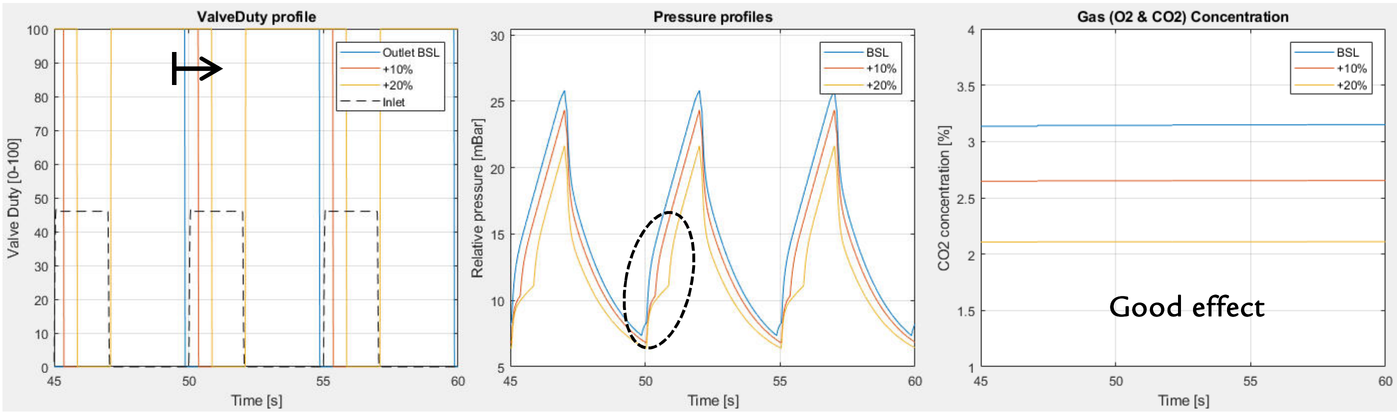
Valve overlap on inhalation phase

Increasing valve overlap in inhalation phase is not efficient in reducing CO2 concentration because replace already low % CO2 air with air at zero concentration. As a further negative effect it changes significantly the mouth pressure profile in both peak value and shape.



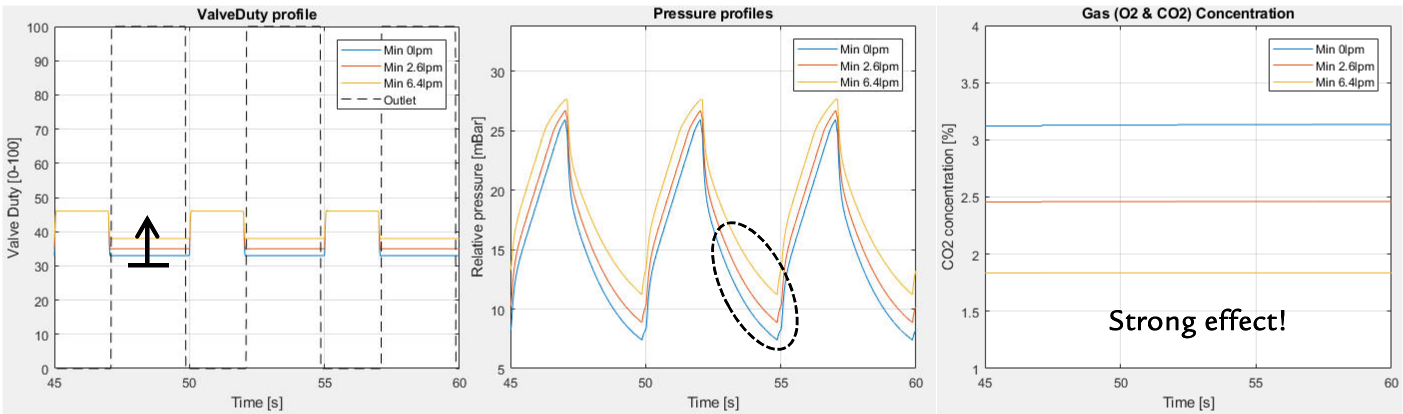
Valve overlap on on exhalation phase

Acting on overlp in exhalation phase is much more efficient due to the action on much higher concentration CO2 air (~ +4% of the inlet).The effect on the pressure curve is reduced in both peak value and general shape.



Valve flow-by

Minimum flow through V1 valve seems the most efficient way to reduce CO2 %. The effect on pressure curve shape is small and **with few lpm is easy to bring CO2 % below 2% threshold**.

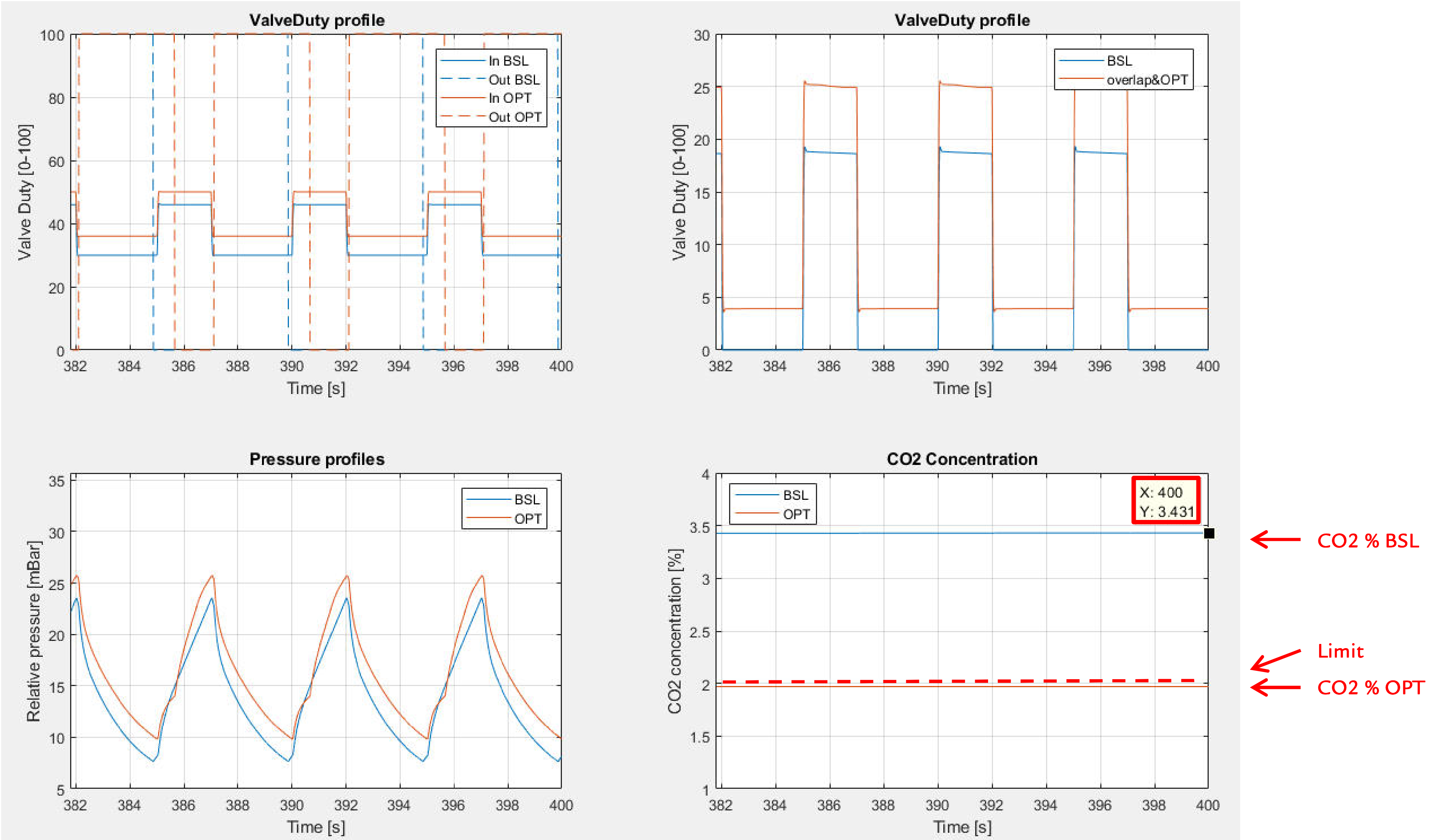


Medical devce uses just flow-by option probably due to the high effectiveness and lowest impact on pressure shape.

CO2 rebreathing Helmet

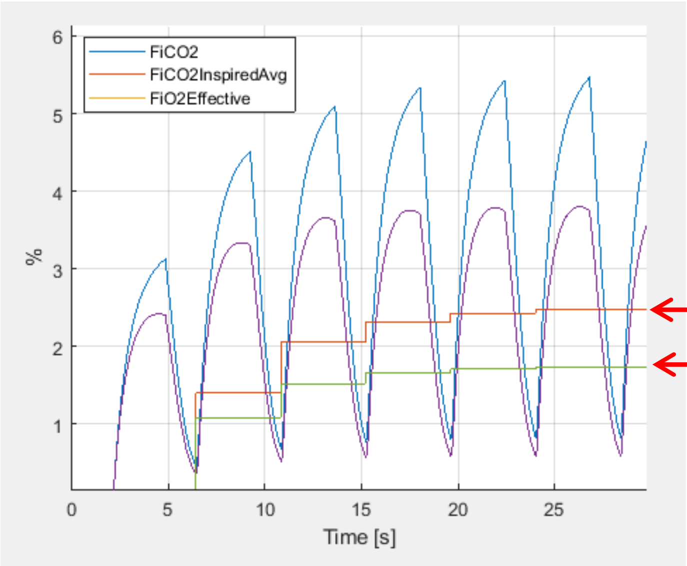
8L have been considered as worst case helmet volume: without any dedicated strategy, CO_2 will stabilize in 5 minutes at **3.4% (vs 3.1% of mask)**, slightly over the mask value but still well over the medical limit.

Applying a small valve overlap and a costant flow through the inlet valve is possible to lower CO_2 % below it's limit without affecting the pressure shape.



CO2 rebreathing – Tidal volume compensation with pressure control

As previously seen, the most efficient way to reduce the Co2 concentration is to keep the inlet valve slightly open during the expiration phase



CO2 % BSL

CO2 % with 1% opening During expiration phase

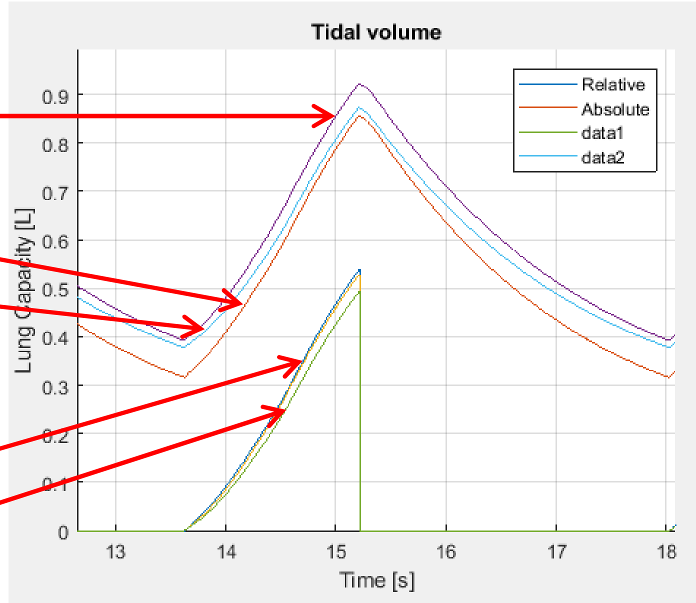
Tidal with 1% opening During expiration phase with compensation

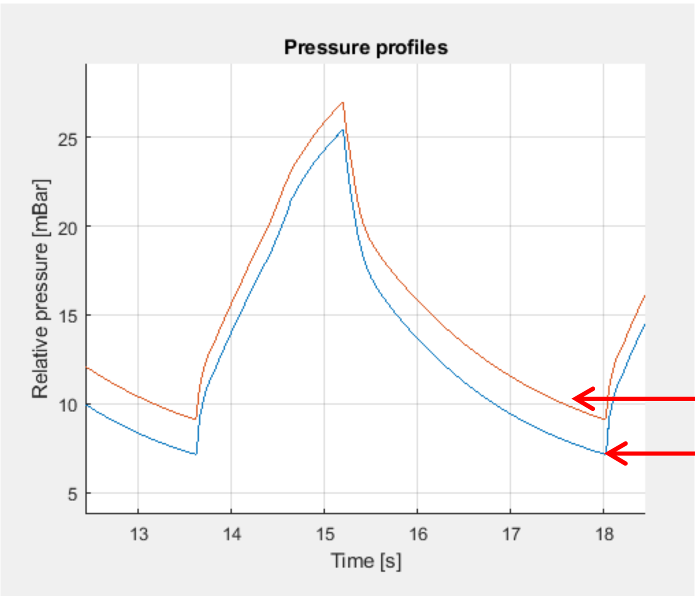
Tidal BSL

Tidal with 1% opening without compensation

Tidal BSL

Tidal with 1% opening without compensation





Mouth P BSL

Mouth P with 1% opening During expiration phase

Because of the inlet valve is kept open during expiration phase, the pressure reached in the expiration phase is higher, resulting in a reduction of the actual tidal volume.

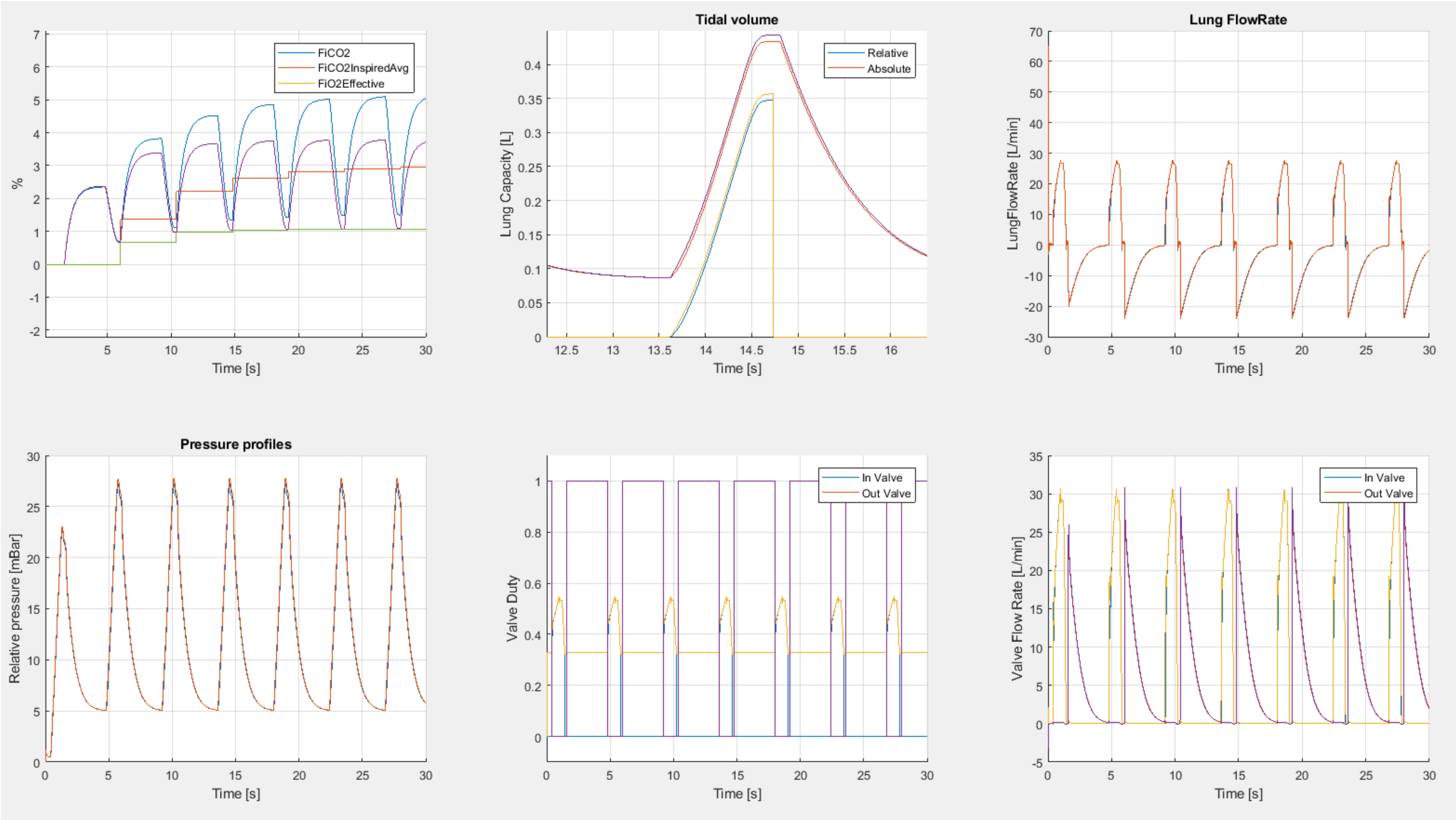
To compensate for this effect, it is sufficient to apply a gain to the pressure target (relative w.r.t. the PeeP pressure).

In case of soft or average lungs a 1% (more than the zero of the valve) duty is enough to reduce the Co2 concentration, while applying a 1.1 gain on the target relative pressure we can compensate the tidal volume.

Stiff lungs requires a higher amount of flowby to reduce Co2, but a smaller gain to compensate the tidal volume, 1.03 (this because the residual pressure at the end of expiration phase changes less with a stiffer lung).

CO2 rebreathing – Tidal volume compensation with flow control

The flow control on the other hand, does not need any target correction in order to keep the tidal volume constant in case of flowby (see below).



FMEA

Four mechanical device will define the flow/pressure level on patient's mouth. **PR1** which is setted to 1000 mbar, **V1** proportional valve, **check** valve setted to a cranking pressure of 80mbar and a **vent** valve setted from 30 to 50mbar.

A single failure inside the ventilator assemblies have been considedered with Vent Trap valve *(which is an external devices*) fitted and not fitted. Worst case have been simulated in order to verify and asses the minimum level of permeability of those valves to be safe.

Simulation results

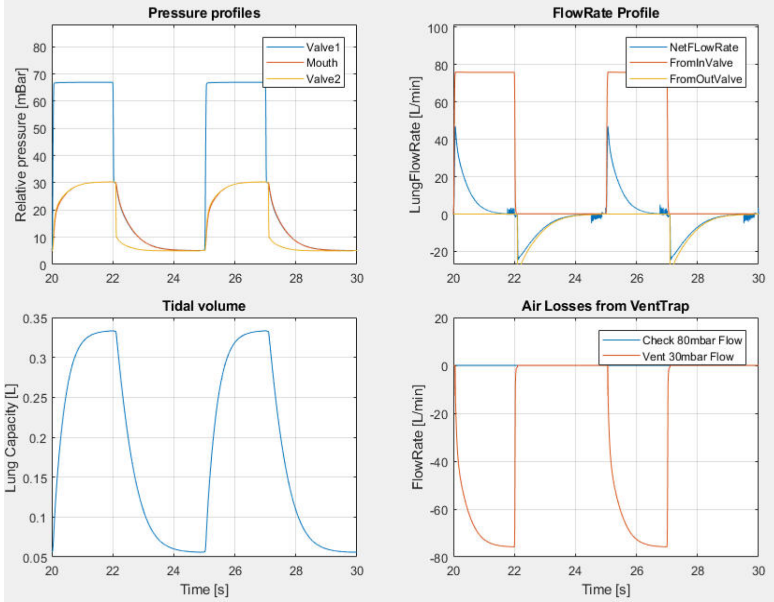
- Vent valve fitted and operative
  - If V1 will not work properly due to control or the valve itself, vent valve will evacuate all flowrate without triggering check valve → **Sim1 next slide**
  - If PR1 will stop working V1 control will correct valve duty to account for change in bounday condition → **Sim3 next slide**
  - If check valve is broken but all other device is working properly will not affect the behaviour of the system → **no need of sim**

- Vent valve NOT fitted or blocked
  - If V1 will not work properly check valve must evacuate all flowrate → **Sim2 next slide**
  - If PR1 will stop working V1 control will correct valve duty to account for change in bounday condition → **Sim3 next slide**
  - If check valve is broken but all other device is working properly will not affect the behaviour of the system → **no need of sim**

<table>
<tr><th colspan="6">FMEA Analysis</th></tr>
<tr><th>PR1</th><th>V1</th><th>Check</th><th>Vent</th><th>Note</th><th>Sim N°</th></tr>
<tr><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>All ok</td><td>-</td></tr>
<tr><td>✓</td><td>✗</td><td>✓</td><td rowspan="3">✓</td><td>Vent to evacuate all exceeding flow</td><td>Sim1</td></tr>
<tr><td>✗</td><td>✓</td><td>✓</td><td>TBD control authority in helping vent evacuate</td><td>Sim3</td></tr>
<tr><td>✓</td><td>✓</td><td>✗</td><td>Vent is sufficient to not trigger check</td><td>-</td></tr>
<tr><td>✓</td><td>✗</td><td>✓</td><td rowspan="3">✗</td><td>Check to evacuate all exceeding flow</td><td>Sim2</td></tr>
<tr><td>✗</td><td>✓</td><td>✓</td><td>TBD control authority in helping check evacuate</td><td>Sim3</td></tr>
<tr><td>✓</td><td>✓</td><td>✗</td><td>No issue if control/v1 and PR works correctly</td><td>-</td></tr>
</table>

FMEA Simulation results Part1

All this simulation have been performed using the stiffest lung characteristics (worst case) and CP valve running with 750mbar of inlet pressure; this case produce an air flow rate through valve **of 88 lpm**. Calculating vent trap pressure drop like a pipe of 0.3mt long with 10mm diam (pessimistic) **we got a loss of 0.1 mbar each 20lpm**.



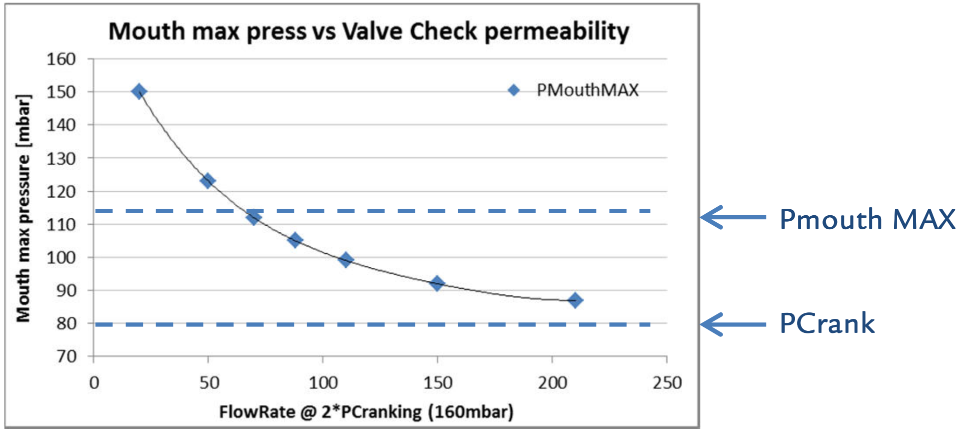
SIM1 (V1 issue, Vent fitted)

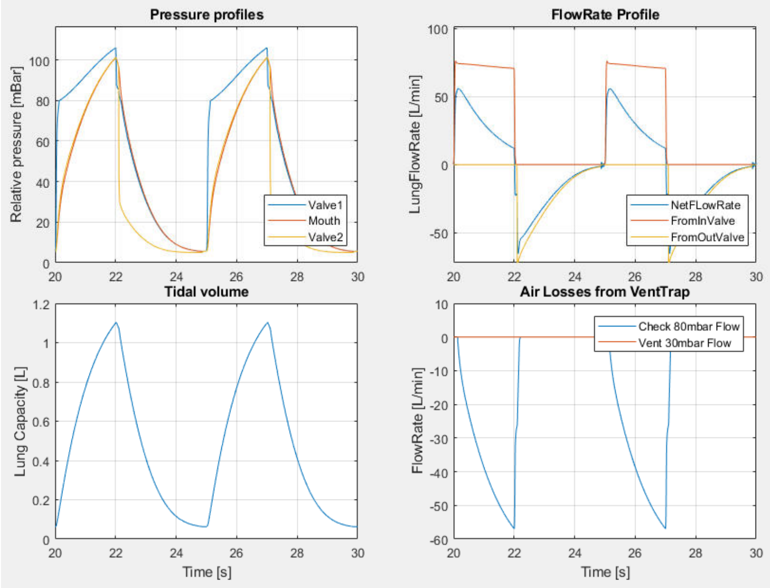
Vent valve with it's high permebility will evacuate all excess of air without triggering mechanical check valve.Flowmeter pressure drop (almost 20mbar) help increasing operating pressure on mechanical check valve without reaching 80mbar of crancking pressure.

In this condition **mouth pressure tend to 31mbar.**

SIM2 (V1 issue, Vent not fitted)

The only protection will be the 80 mbar mechanical valve. Permeability target of this valve have been defined considering 110-120 mbar of maximum mouth pressure (from IIT **Medical feedback**). Target valve must **evacuate around 65 lpm of air at 160mbar pressure (+80 wrt cranking).**





FMEA Simulation results Part2

SIM3 (PR1 issue, pressure control)

Pressure regulator failure have been simulated at time 40sec, providing worst case supply pressure close to 4 bar instead of 0.75 bar working point. No big issue on delivered pressure due to both the authority of the implemented control and due to the low sensitivity of the pressure-compensated valve to the inlet pressure in low flowrate operating point.