# 0-D thermo hydraulic approach for predicting pressure and temperature along HELIOS SHe closed loop under pulsed loads

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# Objectives

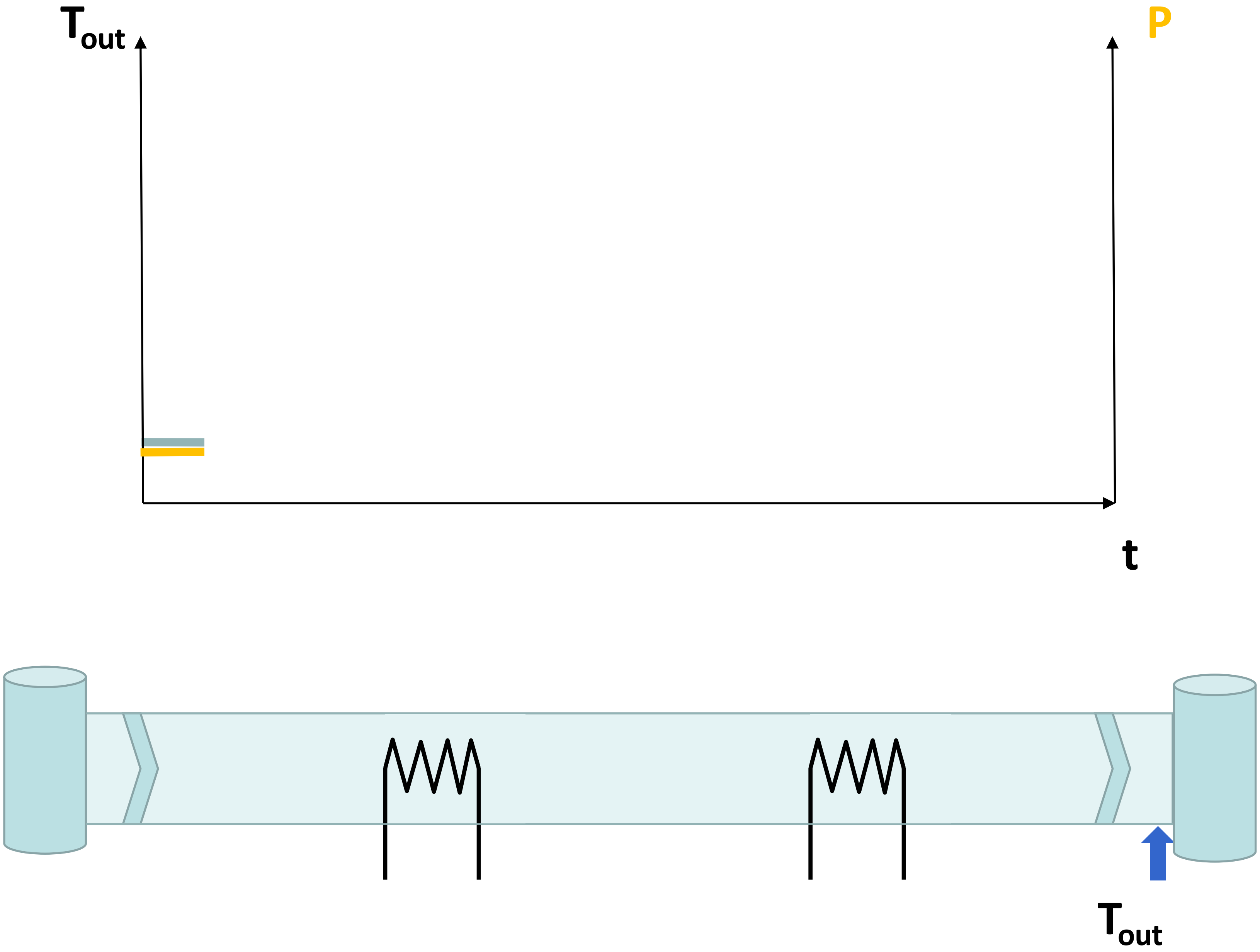
1 Build a simple O-D tool able to describe the time dependent thermo physical properties (Pi(t), Ti(t)) of a flow submitted to pulsed loads. Depending on the accuracy of the 0-D model, it can be implemented in open code as EcosimPro, … Furthermore, it will be an help to analyze/predict the response of pulse loads as the CPU time required would be negligible.

2 A such simple model could be used together with iterative calculations to solve (with some additional assumptions) the inverse problem, e.g. find the time dependent power injected from a time dependent pressure evolution. As pressure reacts instantaneously (no delay due to transit time), this can be used to anticipate the pulse loads arrival at the heat exchanger location.

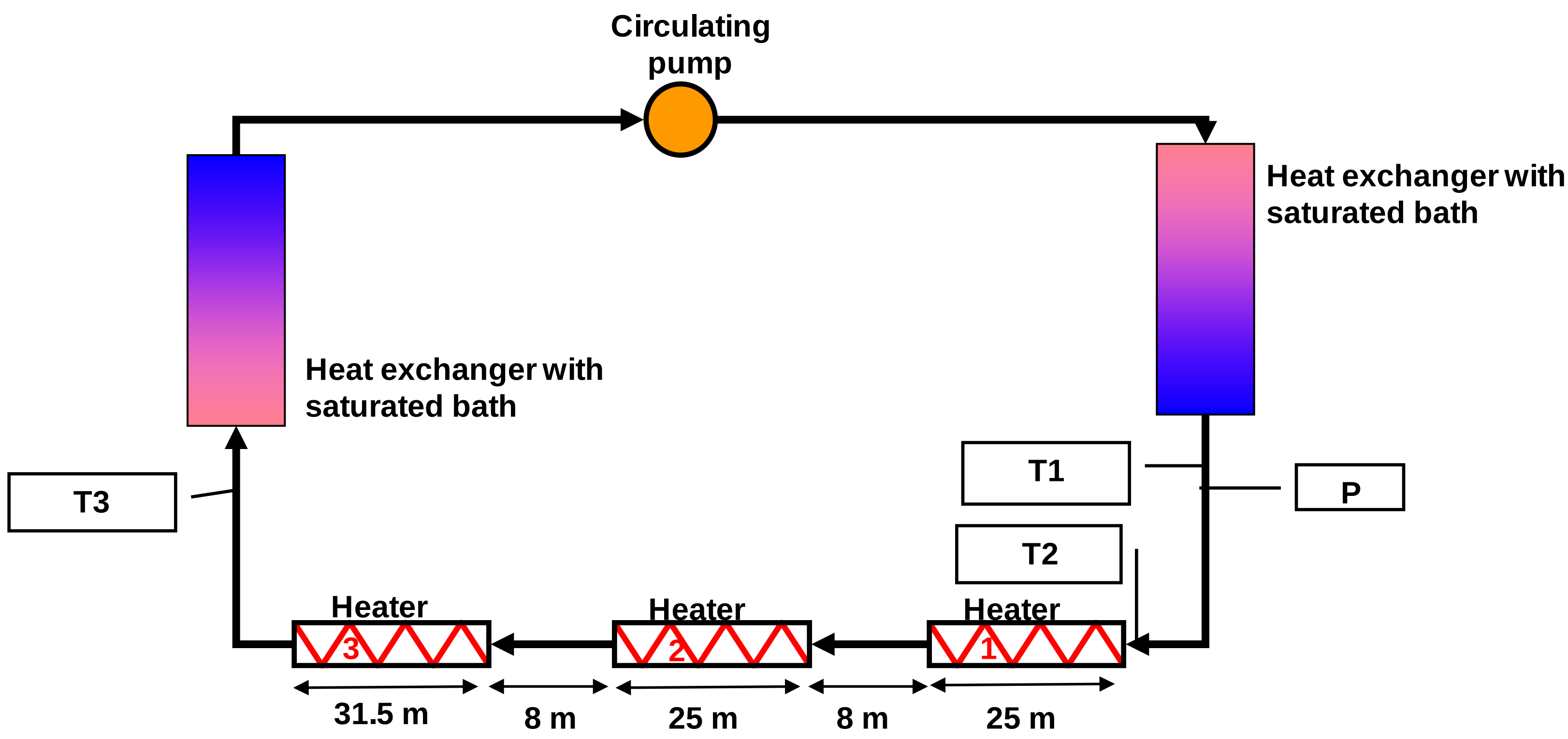

P
t

# Time dependent pressure profile

Just remember that pressure variation only depends on energy variation. So during the power injection, pressure increase is independent of mass flow whereas the plateau and the decreasing time only depend on transit time from the start of the heated zone to downstream the heat exchanger, i.e. mass flow.


T_out
P
t
T_out

# Simplified HELIOS cooling scheme




HELIOS is relevant to an isochoric system including a forced flow, some heaters allowing heat pulses and at least one heat exchanger allowing heat pulses to be removed from the loop.

# Problem to be solved

Input data : mass flow rate, loop geometry and time dependent pulse powers $P_i(t)$

Ouput : Find the time dependent pressure and temperature profiles

# Preliminary remarque

We have seen that transit time seems an important parameter. This transit time depends on considered component geometry.
Is there a simple way to express component transit time ?

Can we choose length and velocity : $t = \frac{l}{v}$ ? Not a good choice !

Right choice implies volume and volumetric flow rate : $t = \frac{V}{\dot{Q}_V} = \frac{V\rho}{\dot{m}}$

Proceeding so, result becomes quasi universal and can be calculated easily.

For example with a density of 132 Kg/m3, 10 l and 100 g/s give 13.2 s (and the same for 100 l and 1 kg/s or 132 s if you consider 1 $m^3$ and 1 kg/s, …)

So remind to say this sensor is located 100 liters downstream the inlet and not 12 m for example !

# 0-D resolution sequence based on superposition principle

Split the loop in various 0-D space components
(volume and time dependent power for each component)

↓

Steady state calculation

↓

Time dependent pressure profile calculation → P(x,t)

↓

Time dependent enthalpy change induced by pressure variation (calculation at the exit of each component)

↓

Time dependent enthalpy change induced by heat input or removed (calculation at the exit of each component)

↓

T(xi,t)

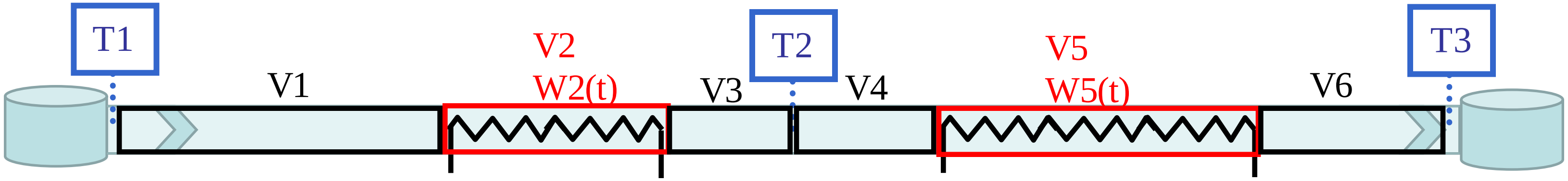
# Choice of volumetric 0-D components

A **component** is defined by its **volume** and eventually the **time dependent power** in case of heated sector.

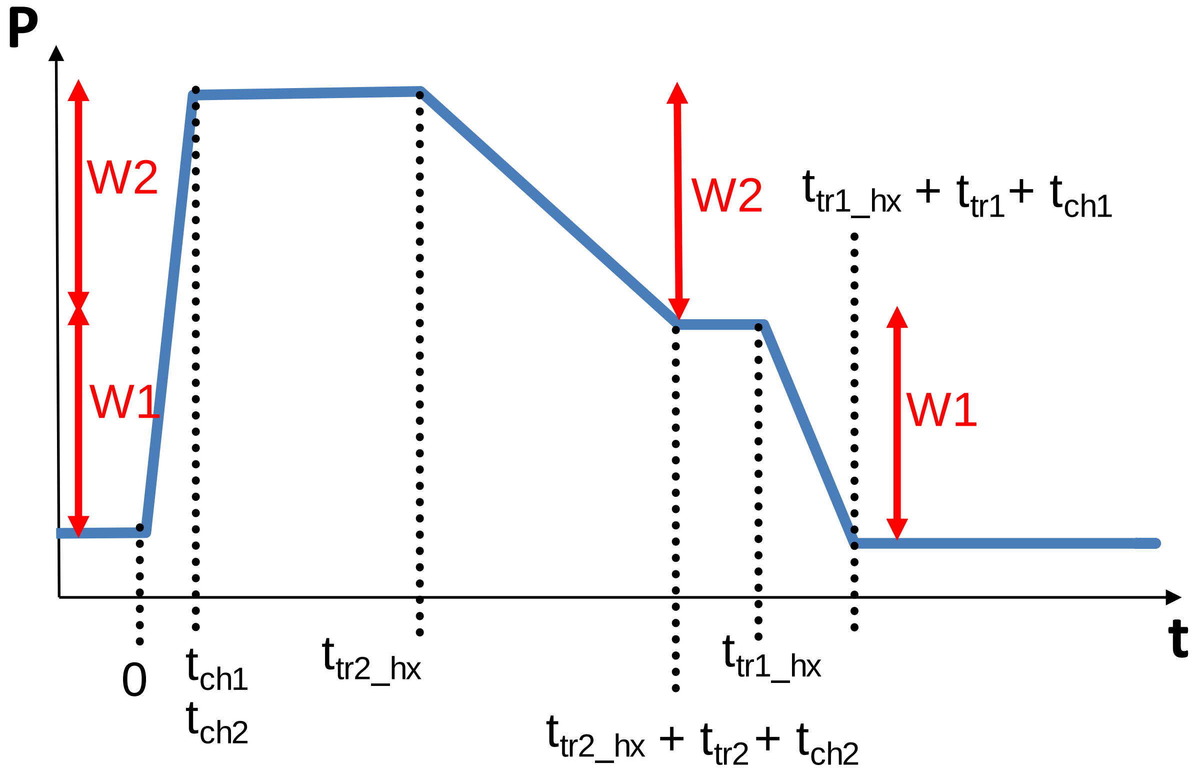
Each heated sector must be considered as a specific component.

So the simplest decomposition consists to build components corresponding to heated sectors and non-heated sectors.

Temperature must be known at the inlet of one component and will be calculated at its outlet. Consequently, to determine a temperature at a specific abscissa, a component must have its outlet at this abscissa. To do this 1 component can be split in 2 components.

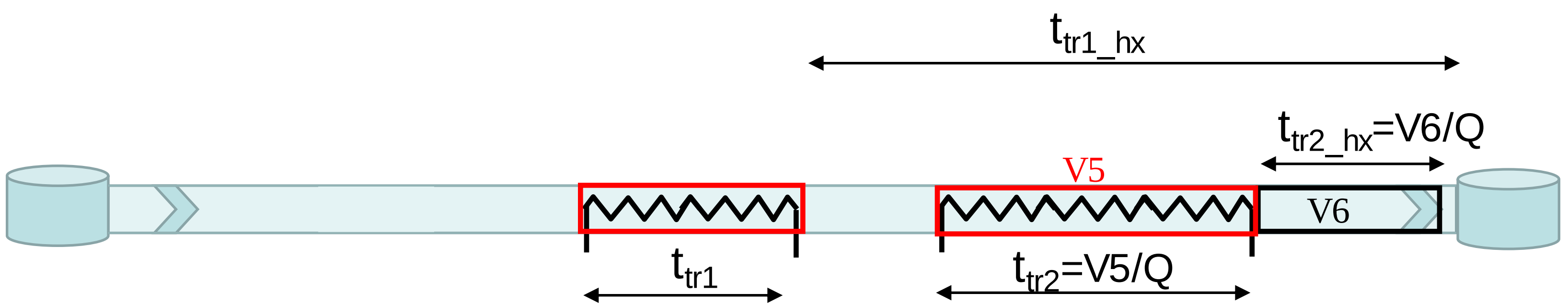


# Time dependent pressure profile : example with two heaters




This example shows that the knowledge of the pressure increase as a function of the heat injected (W1+W2) is sufficient to determine the time dependent pressure profile !

V is the component volume
Q is the volumetric flow rate



# Calculation of the time dependent pressure increase

Thermal loads due to pump work and heat losses are taken into account during the steady state calculation and are supposed to be not affected by the transient loads. The loops is then considered as a closed volume submitted to an isochoric transformation. Applying first principle gives :

$$dU = dQ + dW = dQ$$

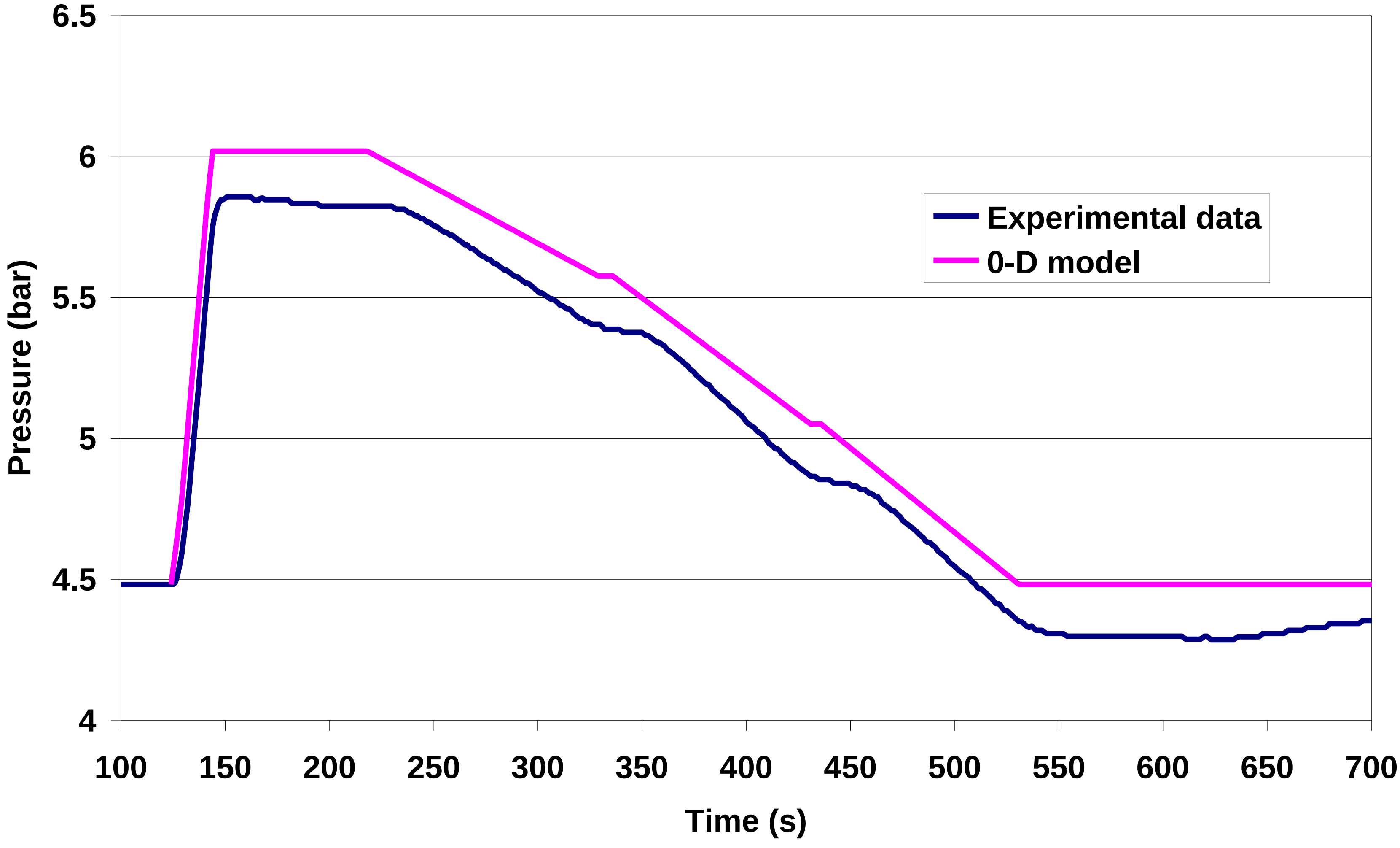
Mass internal energy increase is thus equal to :

$$U_{t+\Delta t} = U_t + \frac{\int_t^{t+\Delta t} W dt}{M_{tot}}$$

Finally the pressure is calculated using the Hepak code using density and internal energy as input data, the former one being constant in this isochoric process.

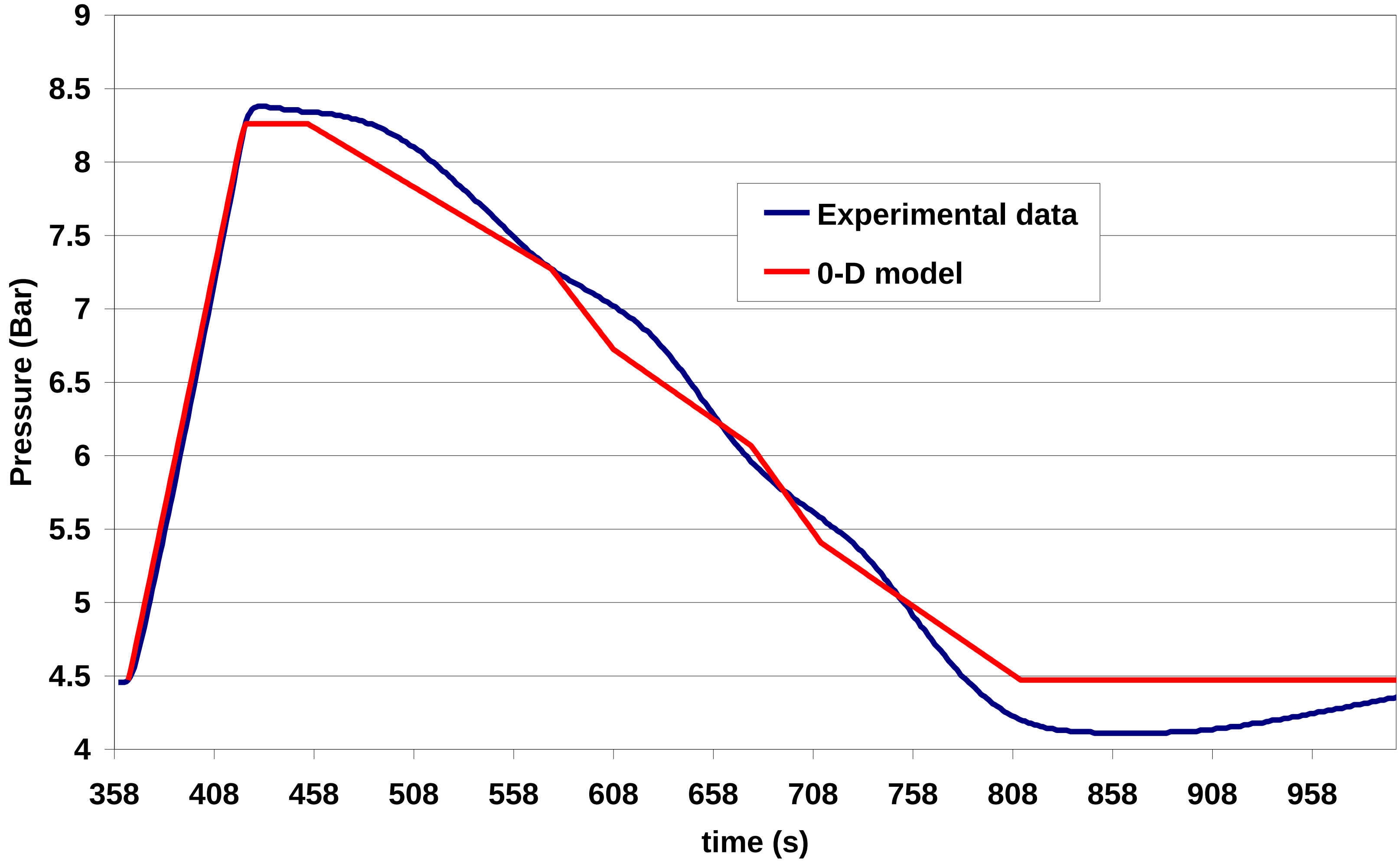
$$P_{t+\Delta t}\left(U_{t+\Delta t}, \rho_{t+\Delta t}\right) \quad with \ \rho_{t+\Delta t} = \rho_t = \rho \quad and \quad U_{t+\Delta t} = U_t + \frac{\int_t^{t+\Delta t} W dt}{M_{tot}}$$

# Time dependent pressure profile : calculated and experimental results




3 simultaneous pulses of 333 Watt - 18 seconds and a mass flow rate of 32 g/s

# Time dependent pressure profile : calculated and experimental results




3 simultaneous pulses of 250 Watt - 60 seconds and a mass flow rate of 32 g/s

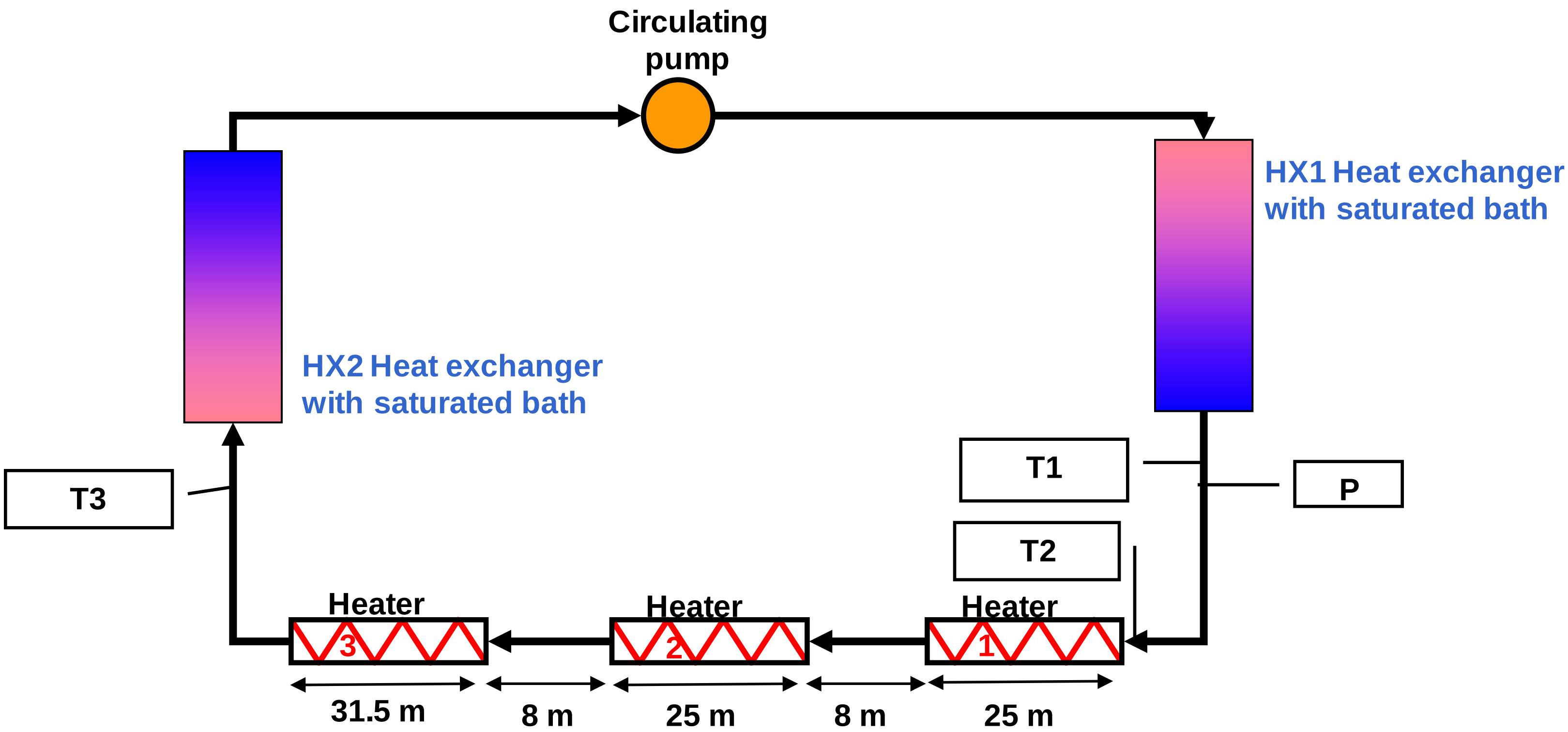
# Calculation of the time dependent temperature profile

Time dependent temperature profile will be different along the line and the global approach adopted for the pressure cannot be used here. Furthermore **variation of pressure as well as heat pulse has large impact on temperature evolution** and each contribution must be considered. Appling once again the superposition principle, we will assume that each contribution can be calculated separately and summed afterwards. Finally, temperature evolution will also depend on temperature profile existing upwind previously (convective effect).

It is assumed that temperature at the inlet of the line has a constant value (equal to bath temperature + a small delta T).

For the point considered, we will **first calculate the contribution of the pressure evolution**.

# Time dependent temperature profile induced by pressure variation



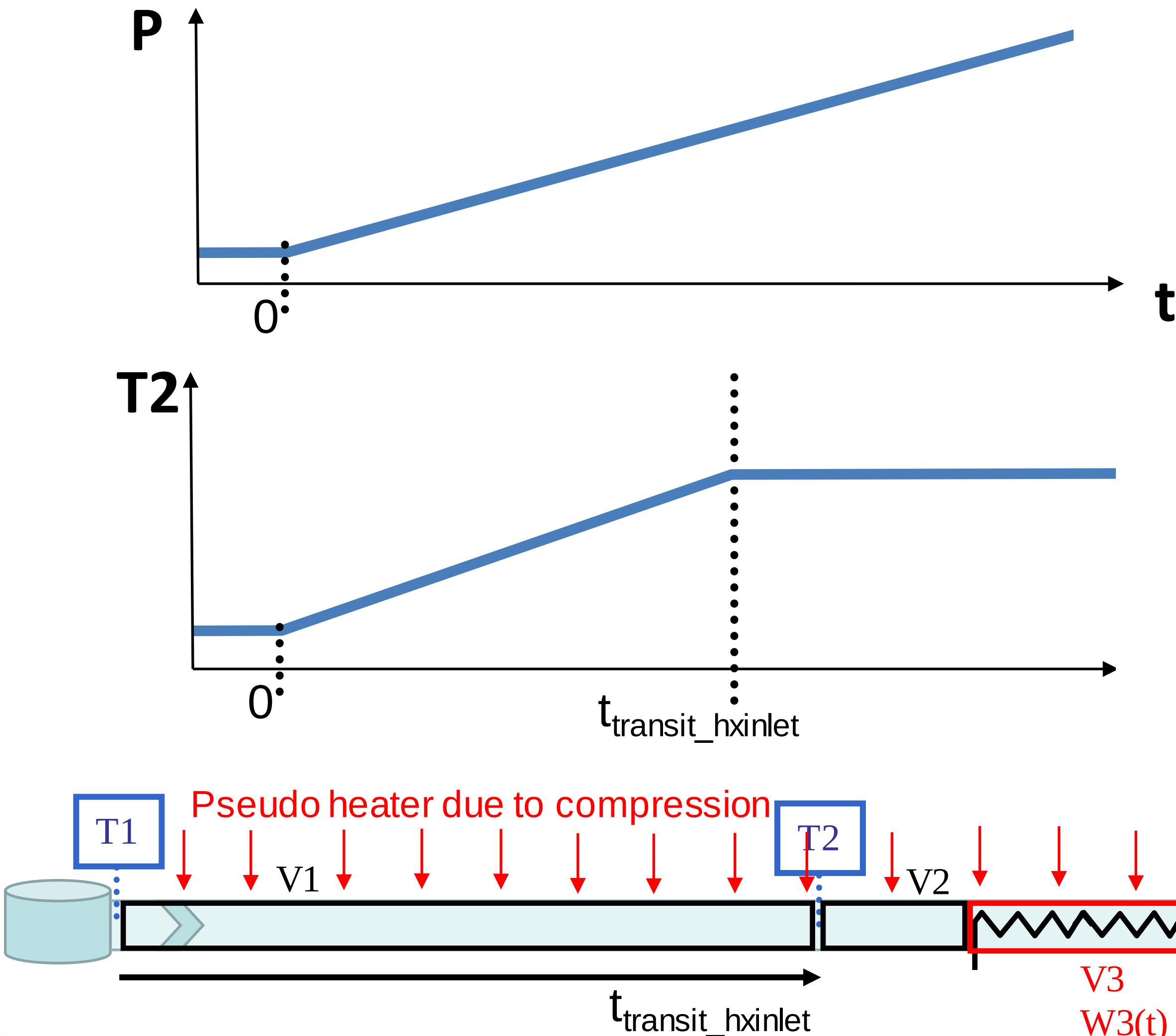

For points located upstream of the heaters (e.g. T1 or T2), the only contribution to temperature change will be pressure change.

# Time dependent temperature profile induced by pressure variation

Compression induced by energy injection (resp. pressure discharge induced by energy extracted from the loop) will heat (resp. cool down) fluid inside the loop.
Variation of pressure can be thus considered as heater (or cold source) uniformly distributed along the loop.
Furthermore, for a constant pressure evolution, temperature change will be limited by the transit time between the inlet heat exchanger (HX1) where outlet temperature is kept constant and the point considered (T2).

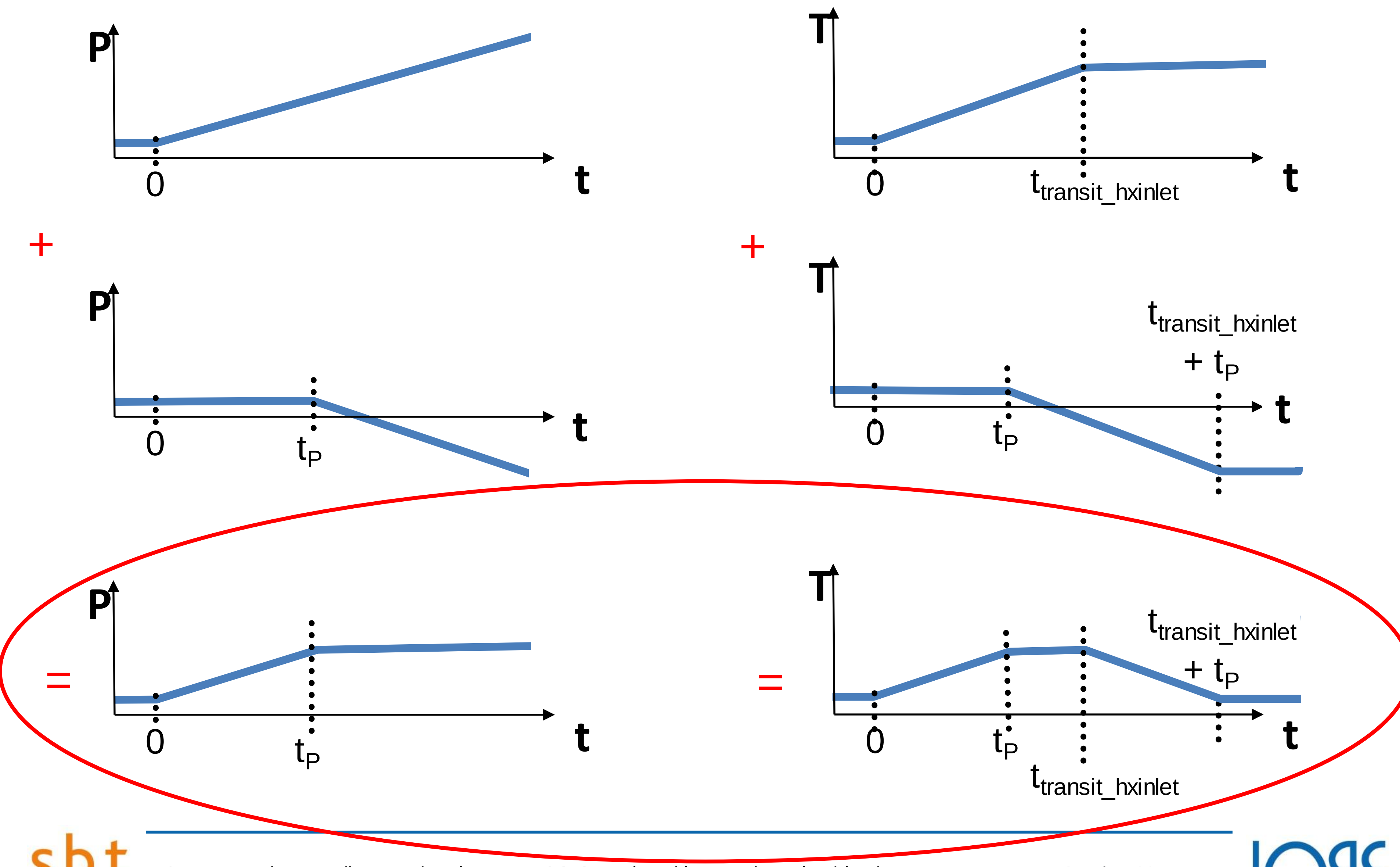
# Time dependent temperature profile induced by pressure variation

Some examples of temperature response to a pressure gradient are shown on following figures.



# Time dependent temperature profile : pressure effect

$t_P < t_{transit\_hxinlet}$



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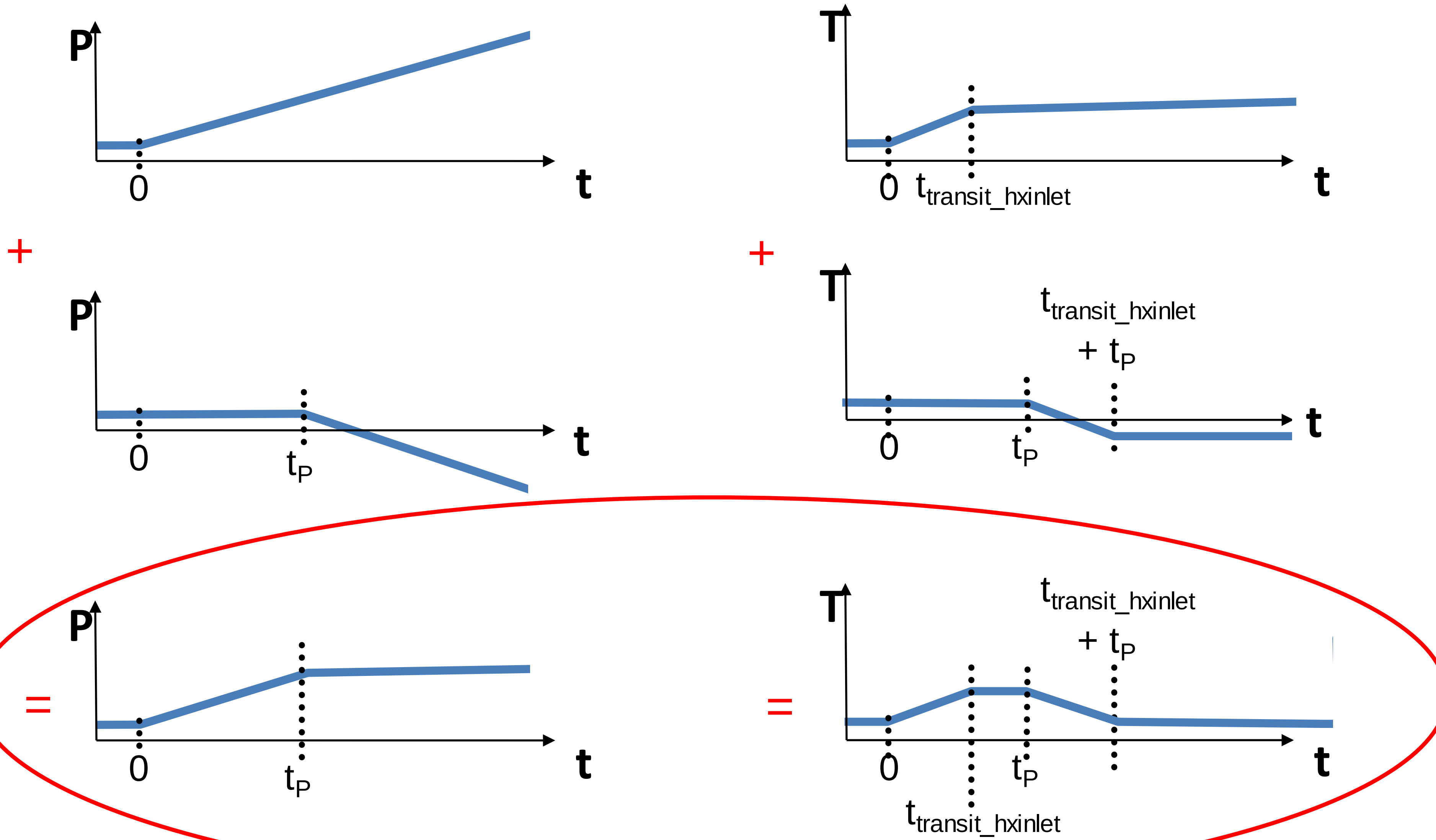
$t_P > t_{transit\_hxinlet}$



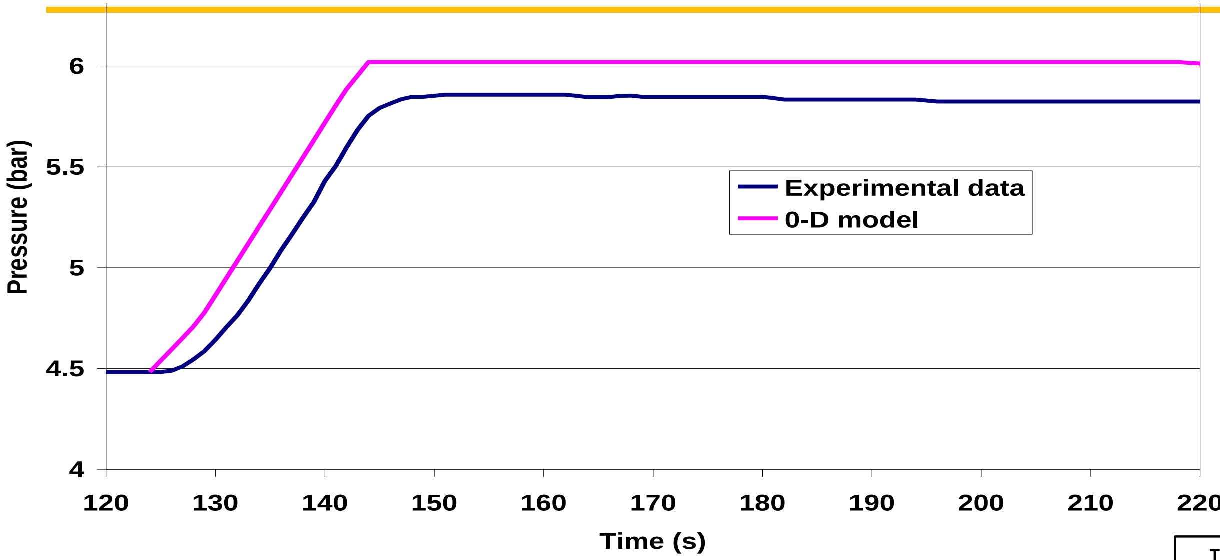
# Time dependent temperature profile induced by pressure variation

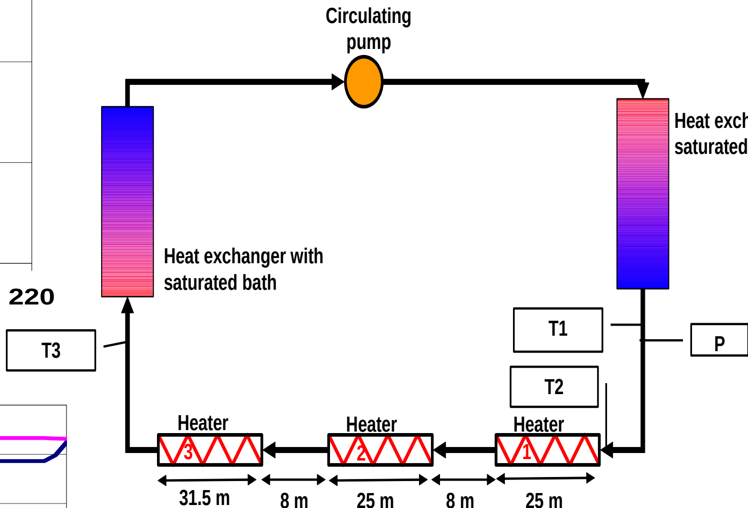
To calculate the influence of pressure variation on temperature, we will consider an isentropic evolution. An isentropic evolution means an evolution both adiabatic and reversible. As the superposition principle will be applied, the contribution of the heat on temperature profile is not taken into account at this stage and the assumption of adiabatic evolution is logical. Furthermore, considering the fact that a compression followed by a discharge to obtain same value of pressure will give "in fine" same value of temperature, reversibility is also logical.

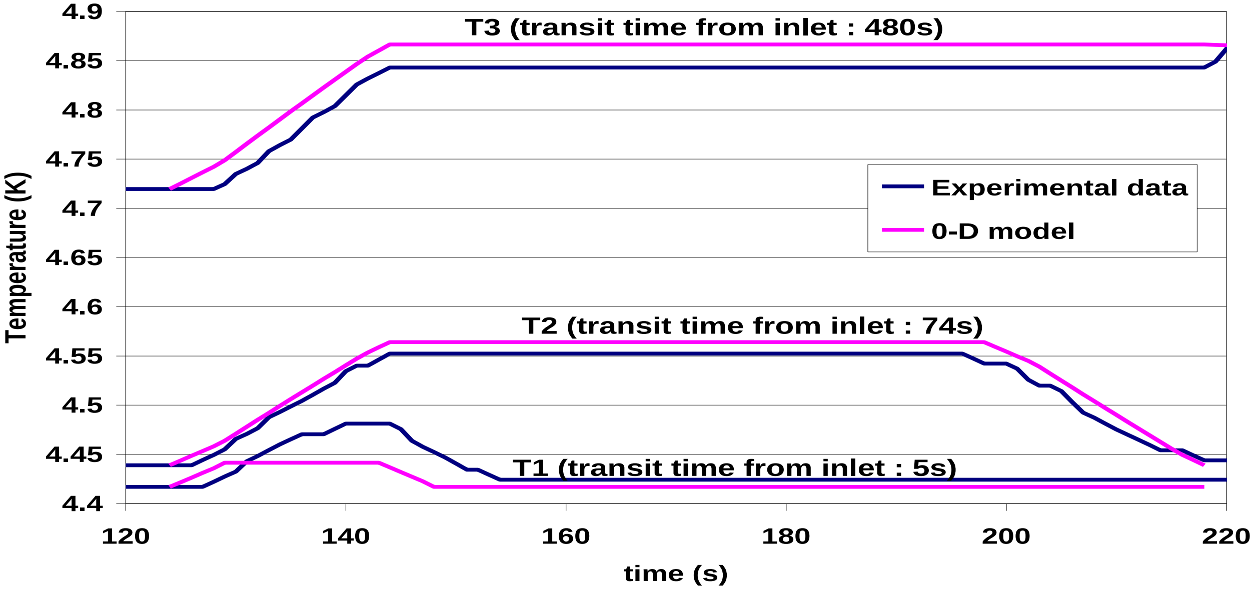
The code Hepak is then used to calculate the time dependent temperature variation induced by pressure change :

$$T_{t+dt} = T\left(P_{t+dt}, S_t\right)$$

# Comparison between experimental data and 0-D model




3 simultaneous pulses of 333 Watt - 18 seconds and a mass flow rate of 32 g/s

# Time dependent temperature profile induced by heat variation

In a 0-D approach, the temperature change will be linked to mass inside the volume and enthalpy change.
To take into account the convection effect, enthalpy at the outlet of the volume must be linked to the value of enthalpy at the inlet with a delay equal to the transit time inside the volume.

So for a non heated volume, the relation is simply

$$H_{outlet}(t) = H_{inlet}(t - t_{transit})$$

While for a heated volume of mass M with a power W initiated at tinit, the resulting equation becomes :

$$H_{outlet}(t) = H_{inlet}(t - t_{transit}) + \frac{\int_{t_{init}}^{t} \frac{1}{L} \int_{0}^{L} W dx dt}{M}$$

Remarque : in any case enthalpy increase along the volume due to steady state heat losses will be added before converting enthalpy in temperature

# Time dependent temperature profile induced by heat variation

Considering a constant spatial repartition and a square temporal power pulse, the previous equation gives :

$$For \quad t_{init} \le t \le t_{OFF} \qquad H_{outlet}(t) = H_{inlet}(t - t_{transit}) + \frac{W(t - t_{init})}{M}$$

Remarque 1 : at this stage, we should say that this relation is only valid for a time lower than the transit time. If the power is maintain for a duration larger than the transit time, then the steady state condition is reached for the considered volume and temperature at its outlet becomes constant

Remarque 2 : when the heater is turn off, the outlet enthalpy remains constant for a duration equal to the transit time leading to the following equation :

$$For \quad t_{OFF} \le t \le t_{transit} \qquad H_{outlet}(t) = H_{inlet}(t - t_{transit}) + \frac{W(t_{OFF} - t_{init})}{M}$$

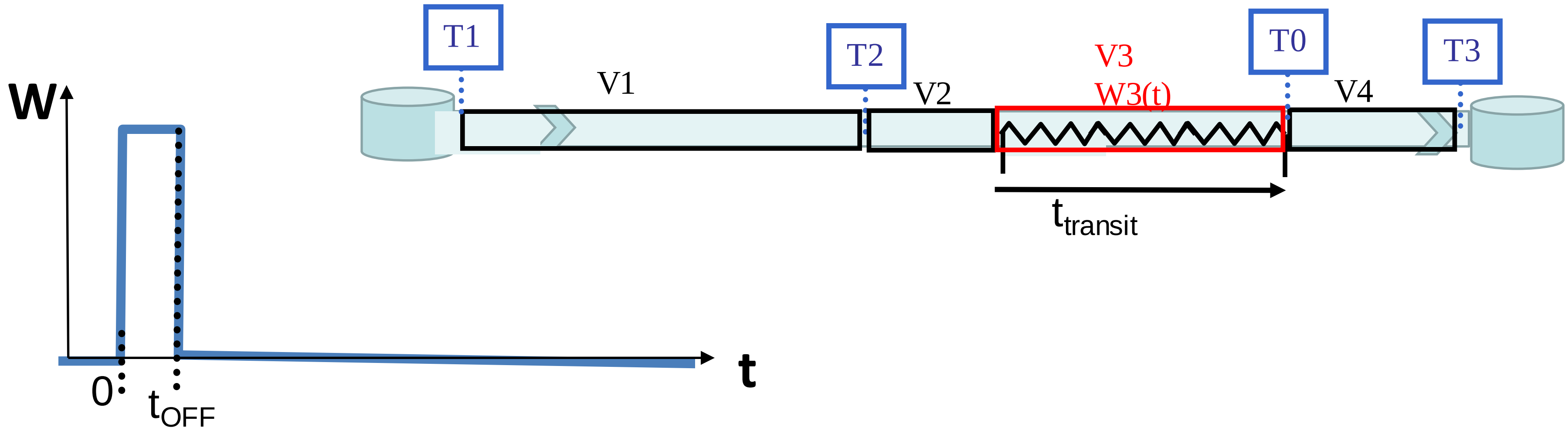
Remarque 4 : After, the enthalpy decreases with the opposite slope of its increase period leading to the following equation :

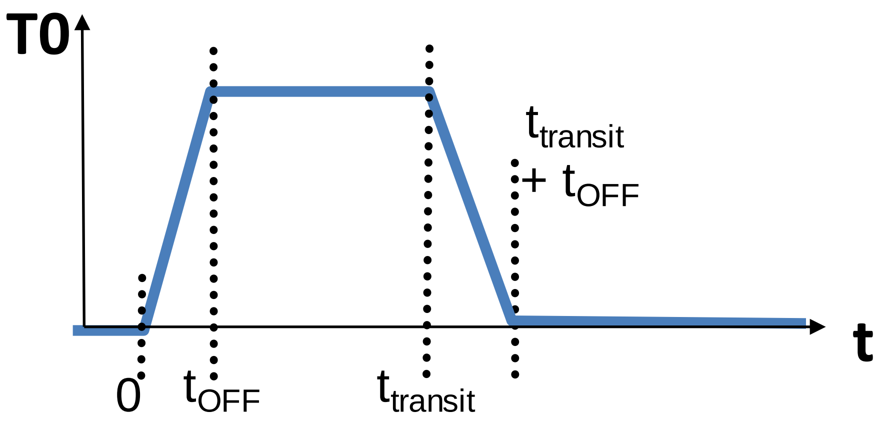
$$For \quad t_{transit} \le t \le t_{transit} + (t_{OFF} - t_{init}) \qquad H_{outlet}(t) = H_{inlet}(t - t_{transit}) - \frac{W(t - (t_{OFF} + t_{transit} - t_{init}))}{M}$$

Remarque 4 : After the heater is turn off from more than the transit time, the pulse is completely evacuated and the equation is the same as a non heated volume :

$$For \quad t \ge t_{transit} + (t_{OFF} - t_{init}) \qquad H_{outlet}(t) = H_{inlet}(t - t_{transit})$$

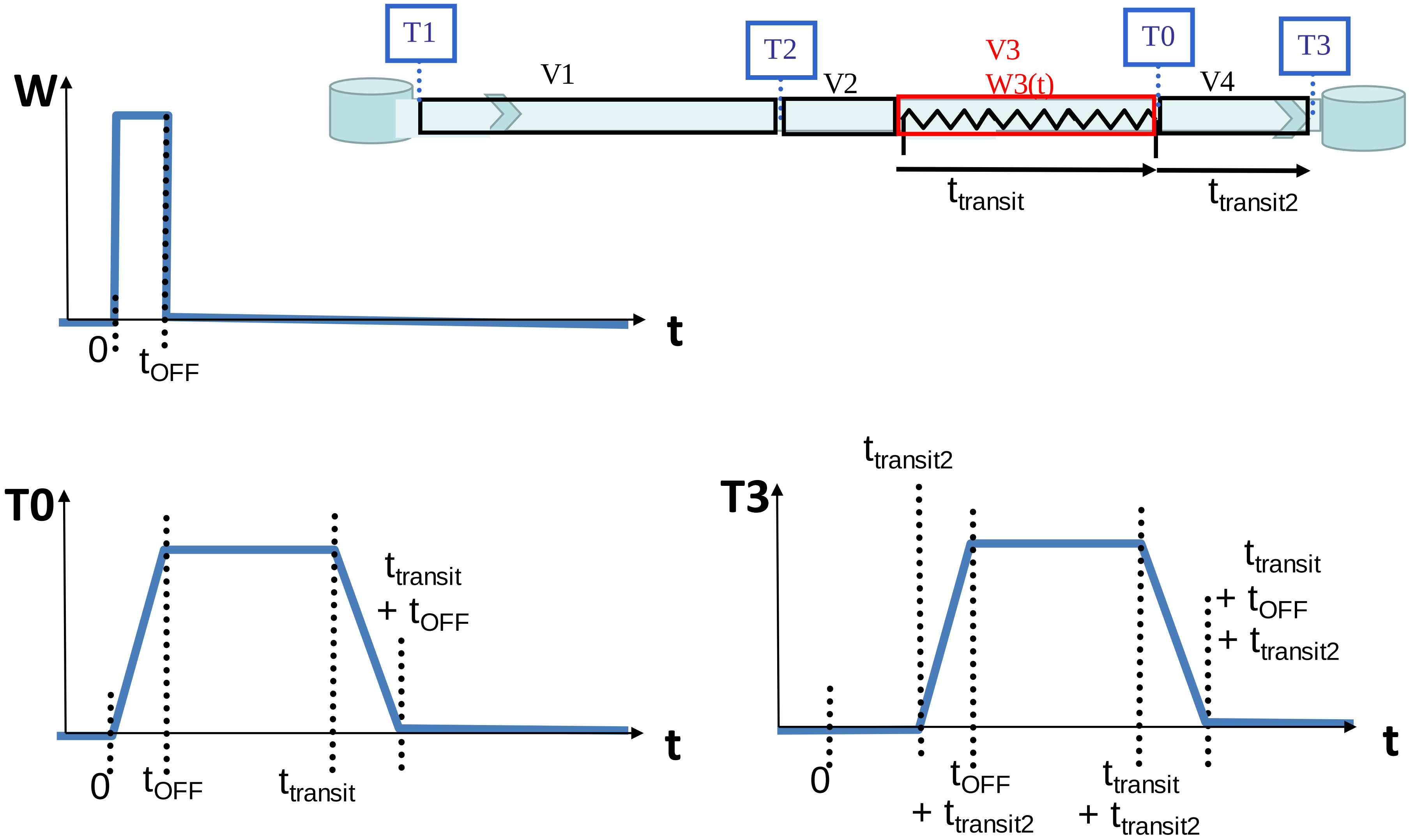
# Time dependent temperature profile induced by heat variation




Temperature profile at the outlet of the heated sector (inlet condition assumed to be constant)

# Time dependent temperature profile induced by heat variation



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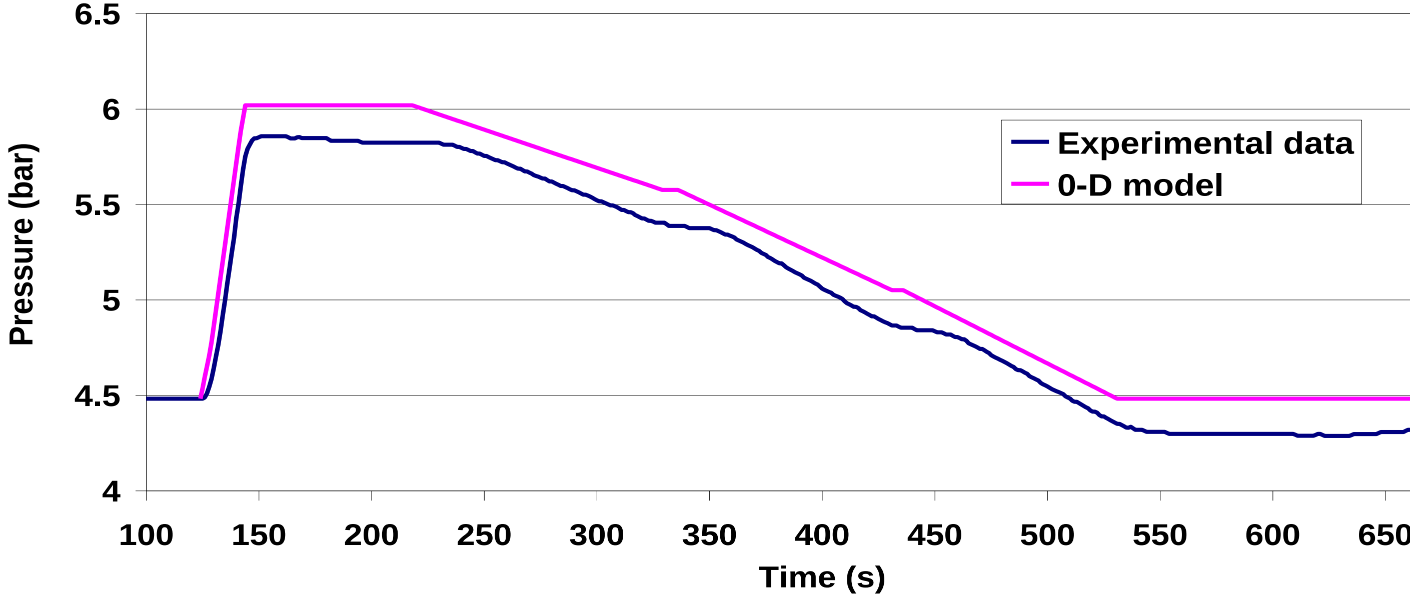


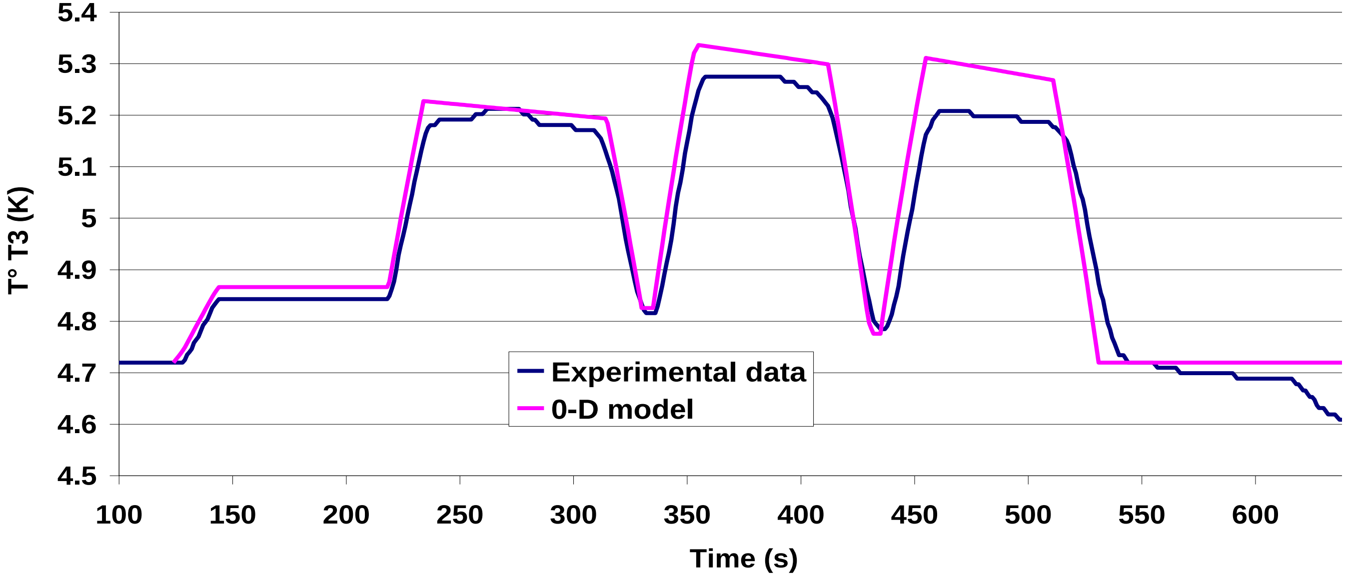

# Summary of 0-D sequence of resolution

Split the loop in various components

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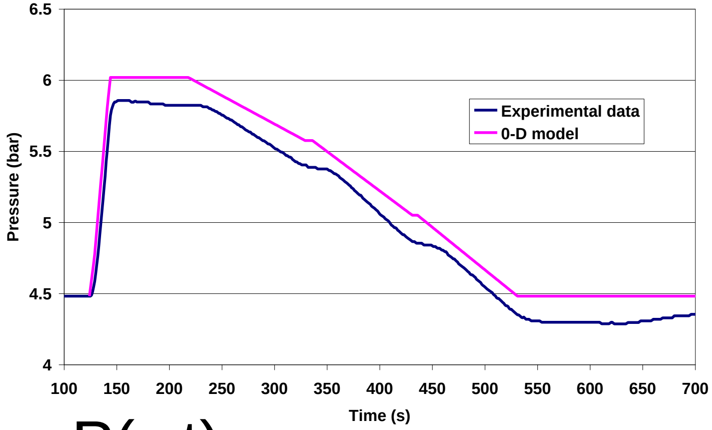
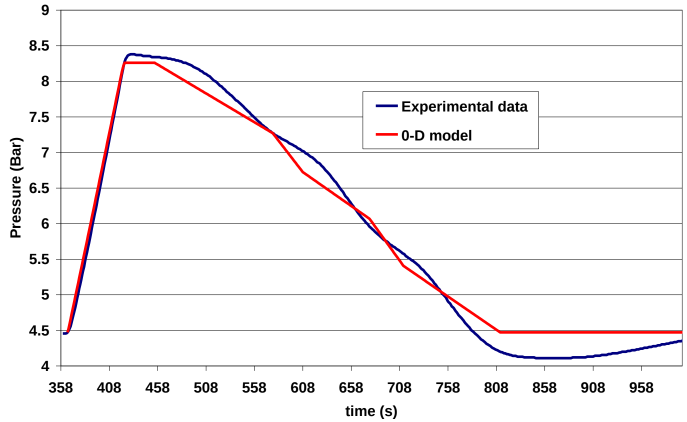
Steady state calculation

↓

Time dependent pressure profile calculation using internal energy variation (trapezoidal shape due to transit time assumed) at constant density → P(x,t)




↓

Time dependent enthalpy change induced by pressure variation assuming isentropic evolution

↓

Time dependent enthalpy change induced by heat input or removed assuming isobaric evolution

↓

T(x,t)

# 0-D sequence of resolution : first improvement

Choice of loop components + Steady state calculation

↓

$$U_{loop(t+\Delta t)} = U_{loop(t)} + \int_{t}^{t+\Delta t} W dt / M_{tot} \longrightarrow P\left(U_{loop(t)} ; \bar{\rho}\right) \longrightarrow H_{outlet}\left(P_{(t)} ; S_{(t0)}\right)$$

↓

$$H'_{outlet}\left(P_{(t)} ; S_{(t0)}\right) = H_{outlet}\left(P_{(t)} ; S_{(t0)}\right) + \Delta H\left(W_{(t-transitoutlet)}\right) \longrightarrow \Delta U_{(t)} = U_{outlet}\left(H'_{outlet(t)} ; P_{(t)}\right) - U_{outlet(t0)}$$

$$H'_{x}\left(P_{(t)} ; S_{(t0)}\right) = H_{x}\left(P_{(t)} ; S_{(t0)}\right) + \Delta H\left(W_{(t-transitx)}\right) \longrightarrow S_{x}\left(H'_{x(t)} ; P_{(t)}\right)$$

↓

$$U'_{loop(t)} = U_{loop(t)} - \Delta U_{(t)} \longrightarrow P'\left(U'_{loop(t)} ; \bar{\rho}\right)$$ ⟶ P(x,t)

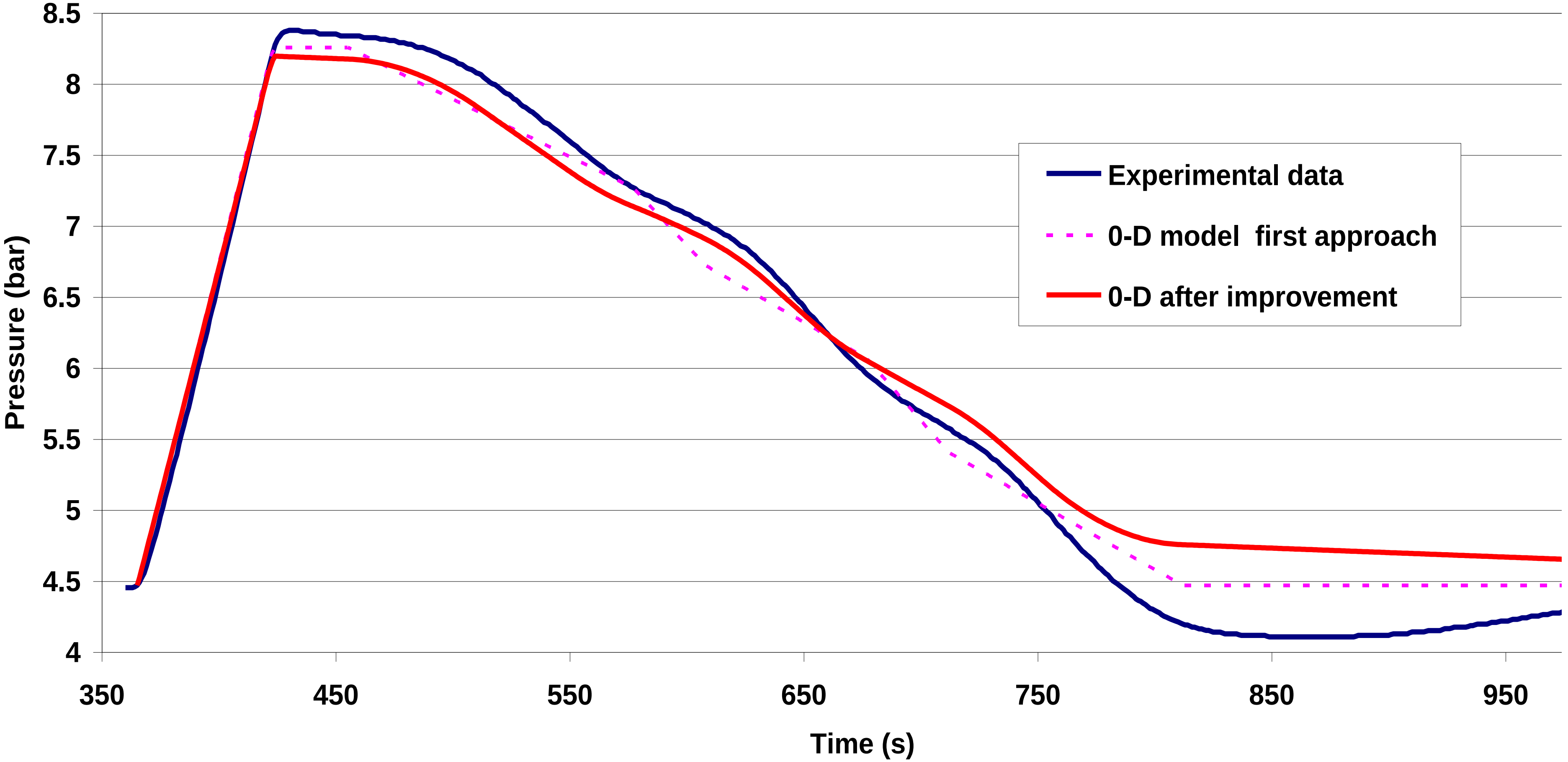
↓

$$T_{x}\left(P'_{(t)} ; S_{x(t)}\right)$$

↓

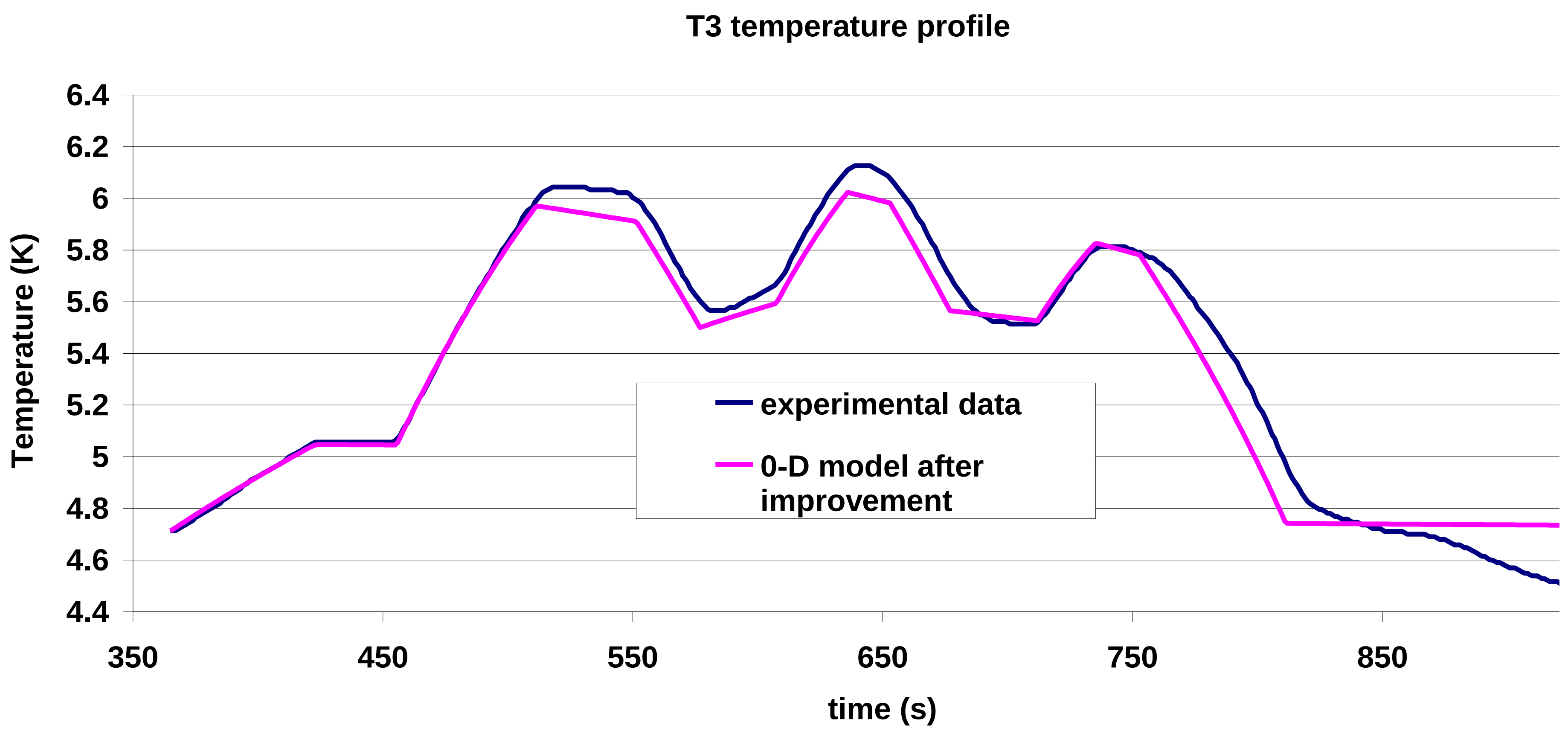
T(x,t)

# Comparison between experimental data and improved 0-D model




3 simultaneous pulses of 250 Watt - 60 seconds and a mass flow rate of 32 g/s

# Comparison between experimental data and improved 0-D model




3 simultaneous pulses of 250 Watt - 60 seconds and a mass flow rate of 32 g/s

# Conclusions :

A very simple 0-D non iterative approach can be used to understand and reproduce correctly the thermohydraulic behavior of a forced flow submitted to distributed heat pulses.

This model may be improved by coupling pressure and temperature effects with an iterative procedure.

Among the limitations of this model, it was not able to reproduce the sub-cooling induced by the pressure decrease.

Finally, latest improvement shows that it could be easily possible to add the saturated bath component with interaction of energy injected inside this bath on both the loop and the bath in order to analyze thermal buffer effect.

Thank you for your attention

# Assumptions :

1) Mass and volumetric flow rates will be considered as constant.

2) Spatial pressure gradient will be considered equal to the steady state case.

3) Power pulses considered here have a constant spatial repartition (W/m) and a square time profile.

4) Heat diffusion through helium or pipe is considered as negligible

5) Equations describing temperature and pressure evolution can be calculated independently, with a superposition principle applied afterward

6) DT between the saturated bath and the outlet of the heat exchanger is supposed to be constant

7) Saturated bath temperature is supposed to be constant

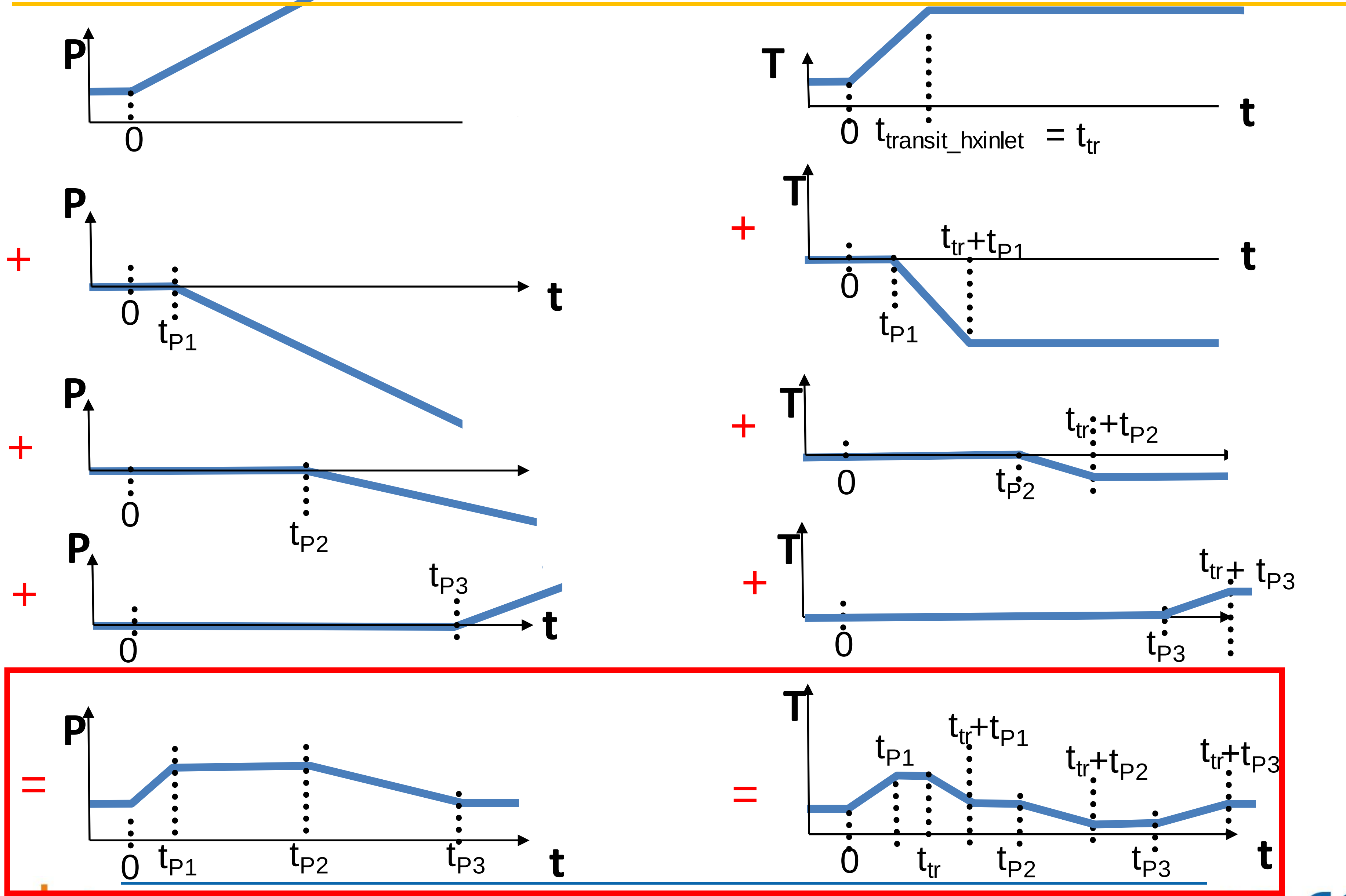
# Steady state calculation

Inlet line temperature, mass flow rate, heat losses and geometry of the line are used in the momentum balance and energy balance equation to determine pressure and temperature in each abscissa.

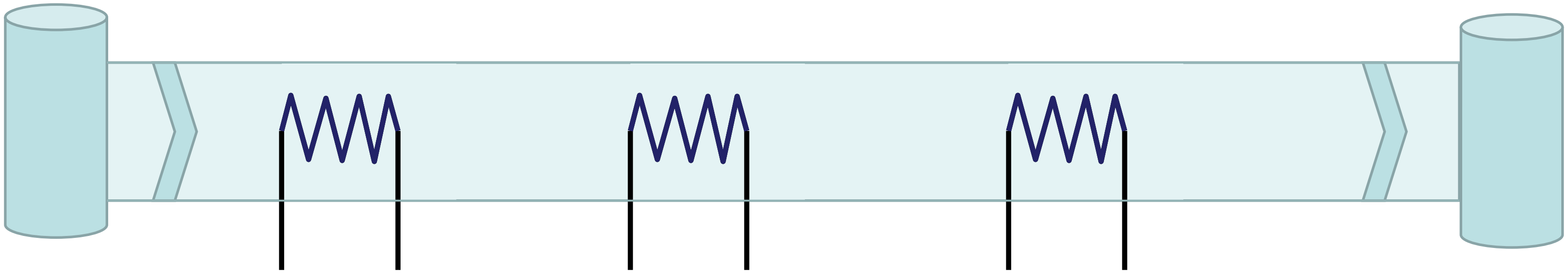
Typically, pressure drop is calculated using some correlations (colebrook correlation for regular pressure drop and adapted correlation for singular pressure drop as elbows or valves), while energy balance is considered as enthalpy balance.

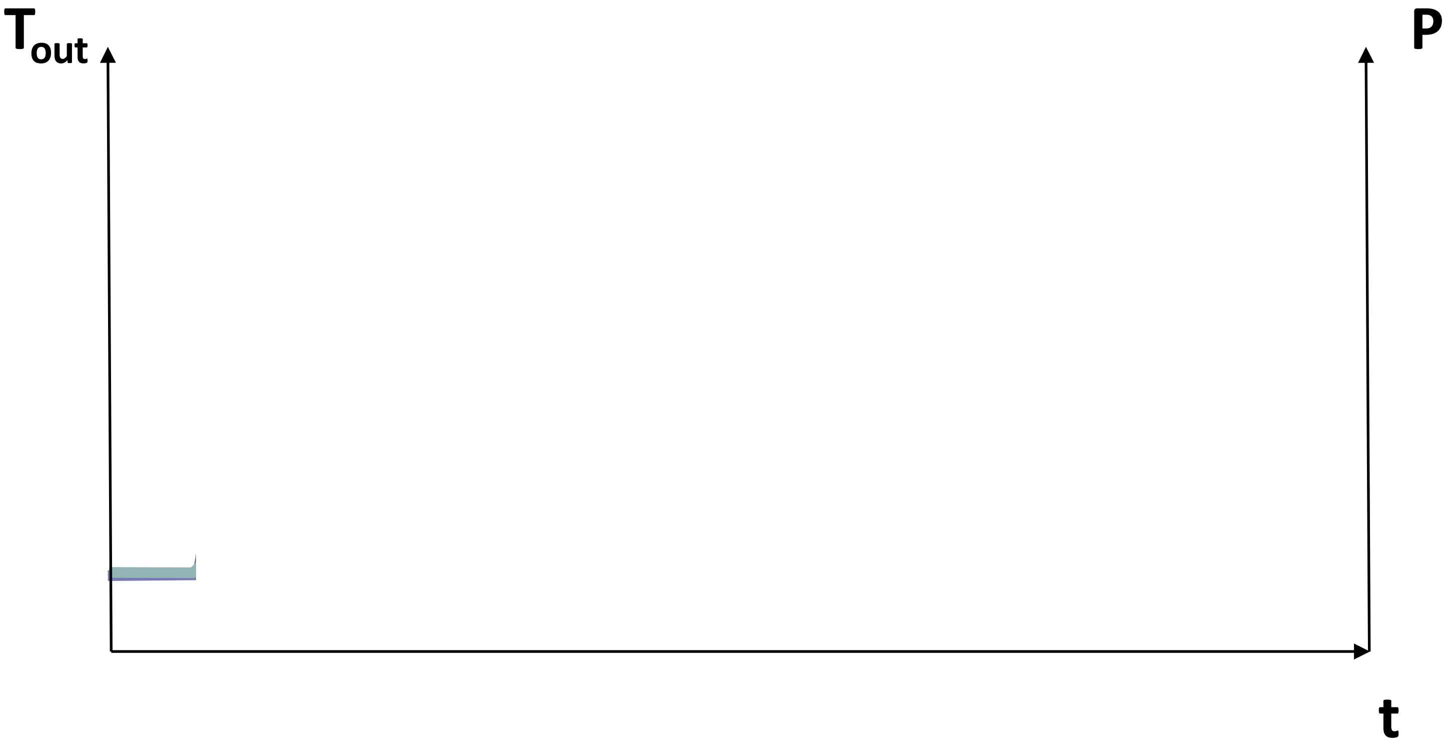
The resolution of pressure and enthalpy in each point is sufficient to solve the thermodynamic problem as these variables are independent.

# Time dependent temperature profile : pressure effect




P
t




Tout
P
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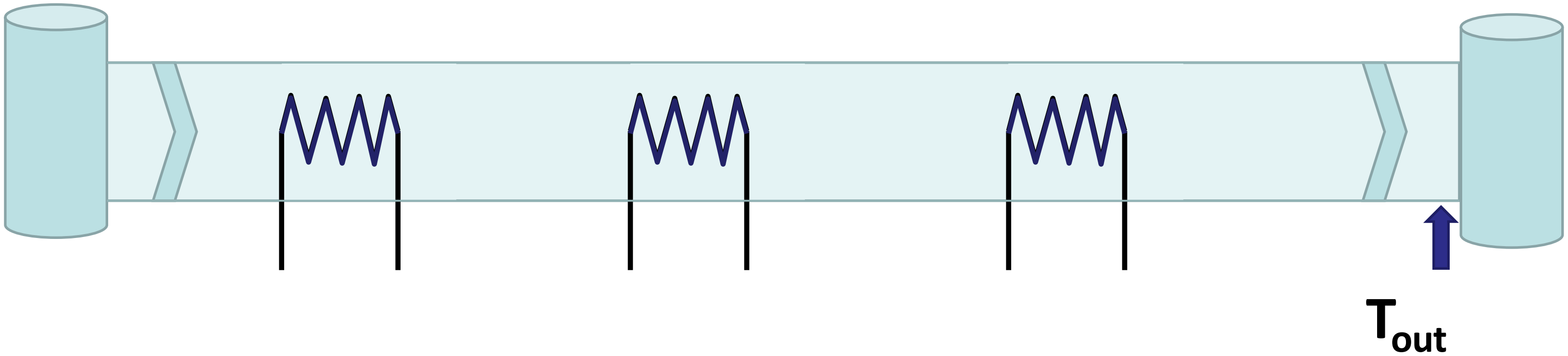
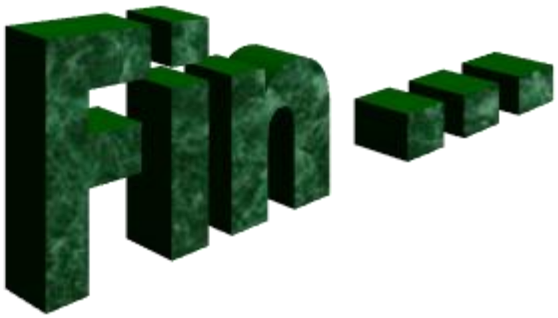

Tout

# Conclusions :

Parmi les nombreuses remarques énergétiques que l'on peut faire, on notera :

- On obtient des extrema de pression (minima ou maxima) à chaque fois que l'énergie extraite dans la boucle est égale à l'énergie extraite en régime stationnaire (ce qui se calcule facilement en additionnant les bilans mDH aux bornes des 2 échangeurs).
- Pendant le pulse de puissance, la température en entrée des échangeurs augmente par effet de montée de pression, ce qui revient à extraire plus de puissance de la ligne et donc à diminuer un peu l'impact du pulse de chaleur en terme d'accroissement de pression.



# Evolution temporelle de la pression: remarque finale

Rmq1 : la connaissance de la montée en pression en fonction du temps peut donc dans la plupart des cas être un indicateur de l'énergie déposée sur la ligne en fonction du temps, par contre cela n'est pas suffisant pour remonter à la répartition spatio-temporelle de la puissance injectée au cours du temps (deux secteurs de longueurs différentes et éventuellement disposés à des endroits différents de la ligne) pouvant ainsi induire la même montée en pression si la puissance totale déposée sur chaque secteur est identique et synchrone.

Rmq2 : Pour retrouver le profil spatio-temporelle de puissance, on peut s'aider du temps de plateau et de la courbe de descente, qui, avec la connaissance du débit devraient permettre de localiser le début et la fin de la zone chauffée, ce qui permettrait ensuite de fixer de manière non ambigüe la valeur de celle-ci au cours du temps.