Fluid mechanical response of a pulse tube cryocooler: modelling and experimental validation

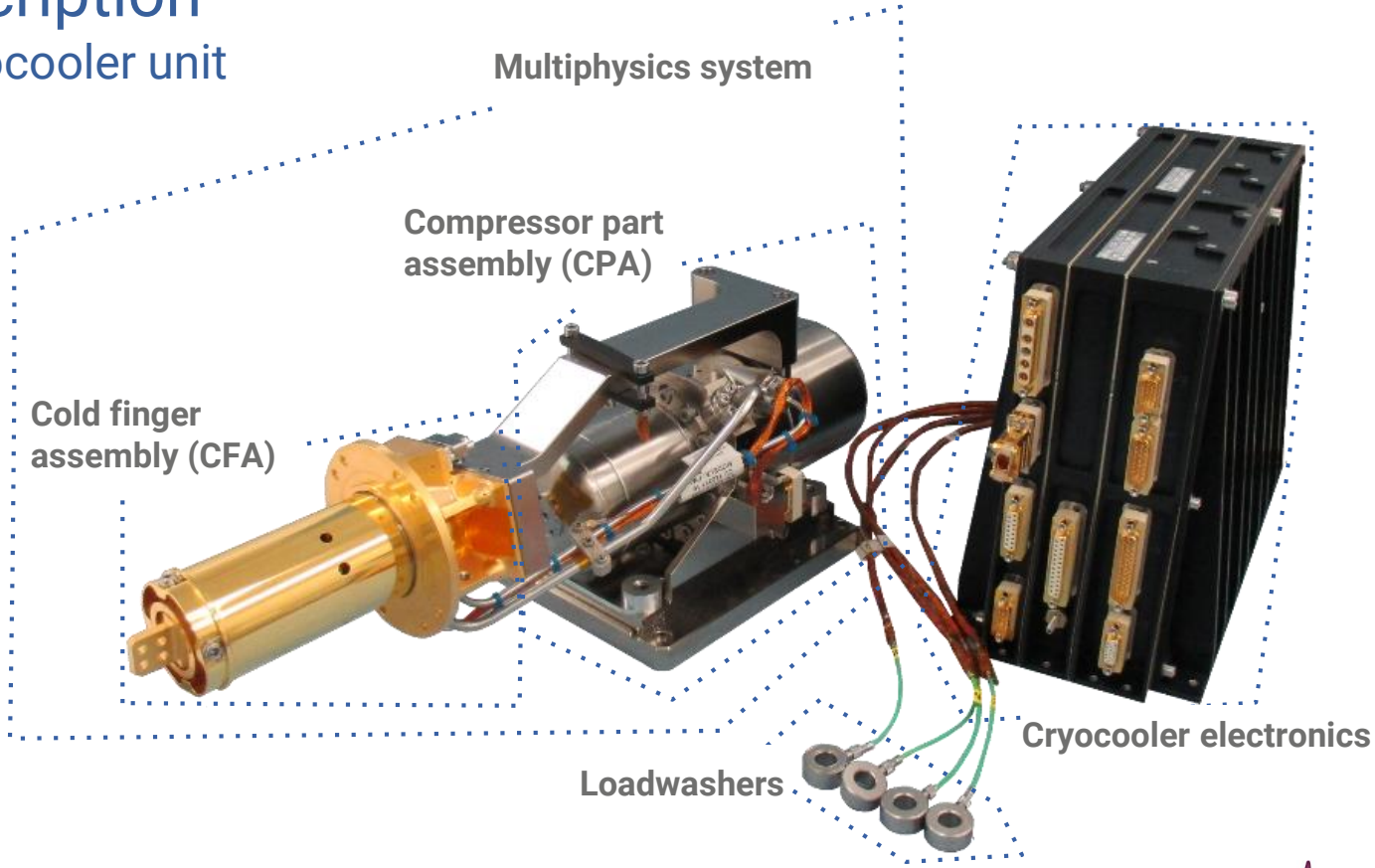
K. Lauzier[1,2], F. Bribiesca-Argomedo[2], J.-Y. Gauthier[2], S. Sesmat[2], X. Lin-Shi[2] and D. Lopes[1]

[1] Space Department, Air Liquide Advanced Technologies
[2] INSA Lyon, AMPERE Laboratory, CNRS, France

System description

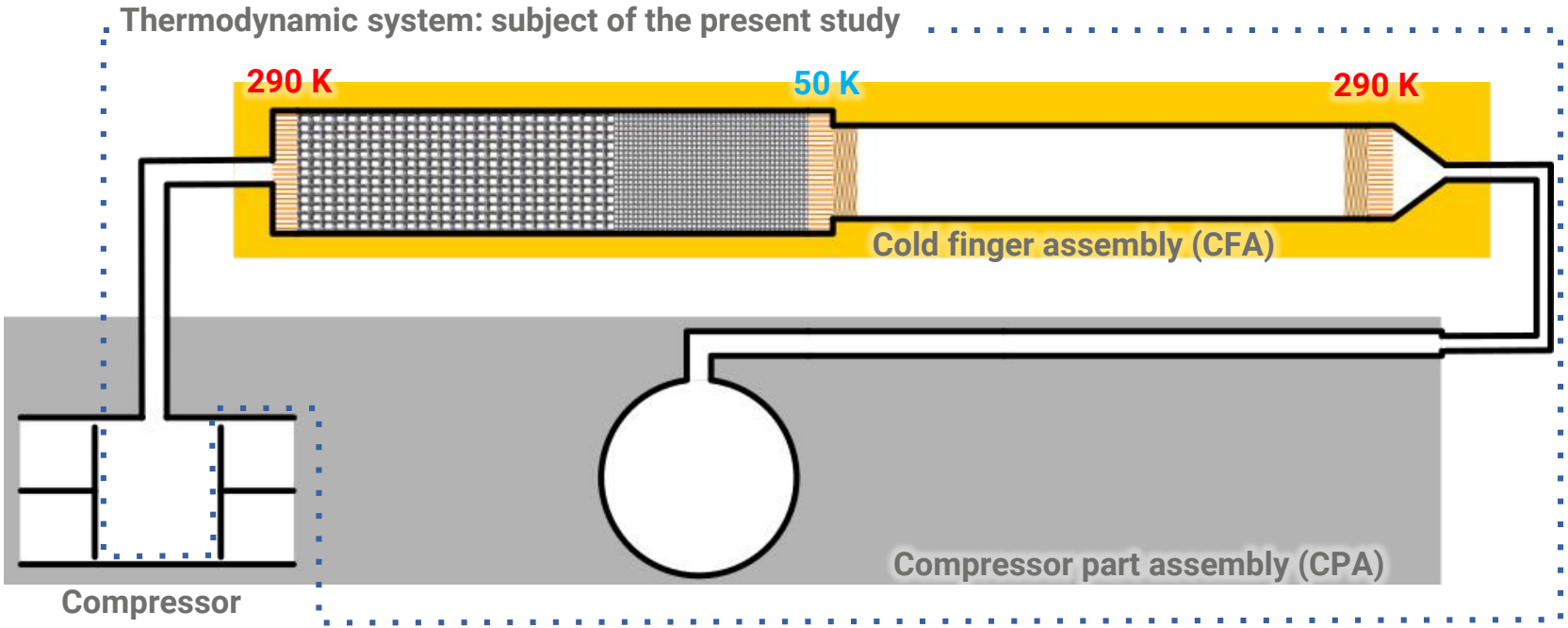
A pulse tube cryocooler unit

TRL9
Max. input power : 160W
Mass: 7.3 kg
Temperature : 50K – 80K
Heat lift: 2W – 8W



System description

The thermodynamic system



1

Why to model pulse tube cryocoolers?

Why model pulse tube cryocoolers?

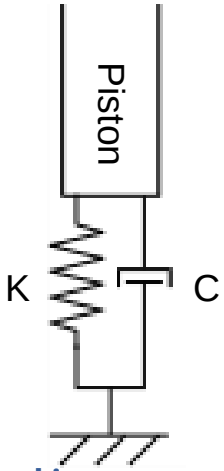
Why and how have others done it?

Predict and improve thermodynamic performances

Why model pulse tube cryocoolers?

Why and how have others done it?

Predict and improve thermodynamic performances

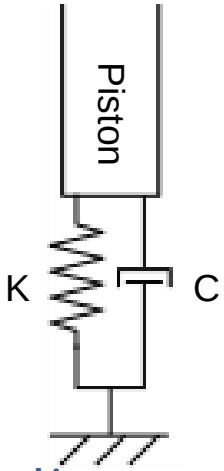


Predict and improve compressor performances

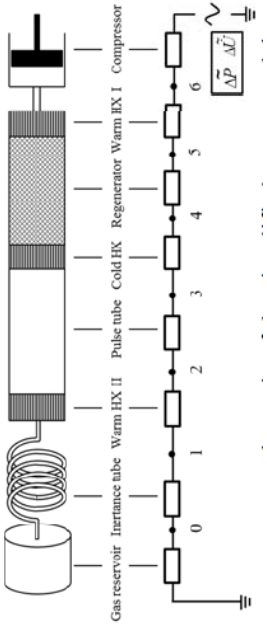
Why model pulse tube cryocoolers?

Why and how have others done it?

Predict and improve thermodynamic performances



Predict and improve compressor performances



Predict and improve system performances

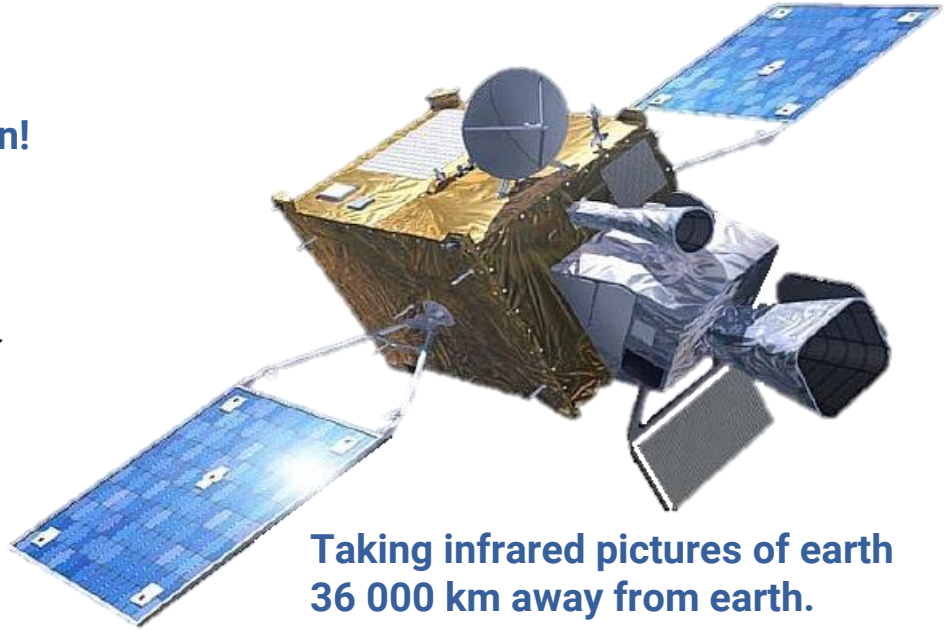
Why model pulse tube cryocoolers?

Why do we do it?

System vibrations prediction and reduction!

Stringent vibration requirements :

- From $f_0 \approx 50\ Hz$ to $10 \cdot f_0 \approx 500\ Hz$
- $\forall f, F < 0.3\ N$



Taking infrared pictures of earth 36 000 km away from earth.

Neighboring instruments sensitive to vibrations (spectrometers,…)

Why model pulse tube cryocoolers?

Why do we do it?

Vibrations

Why model pulse tube cryocoolers?

Why do we do it?

Sources

- Motors/pistons unbalance
- Fluid-structure interaction

&

Non linearities

- Real physical phenomena

&

Frequency behavior

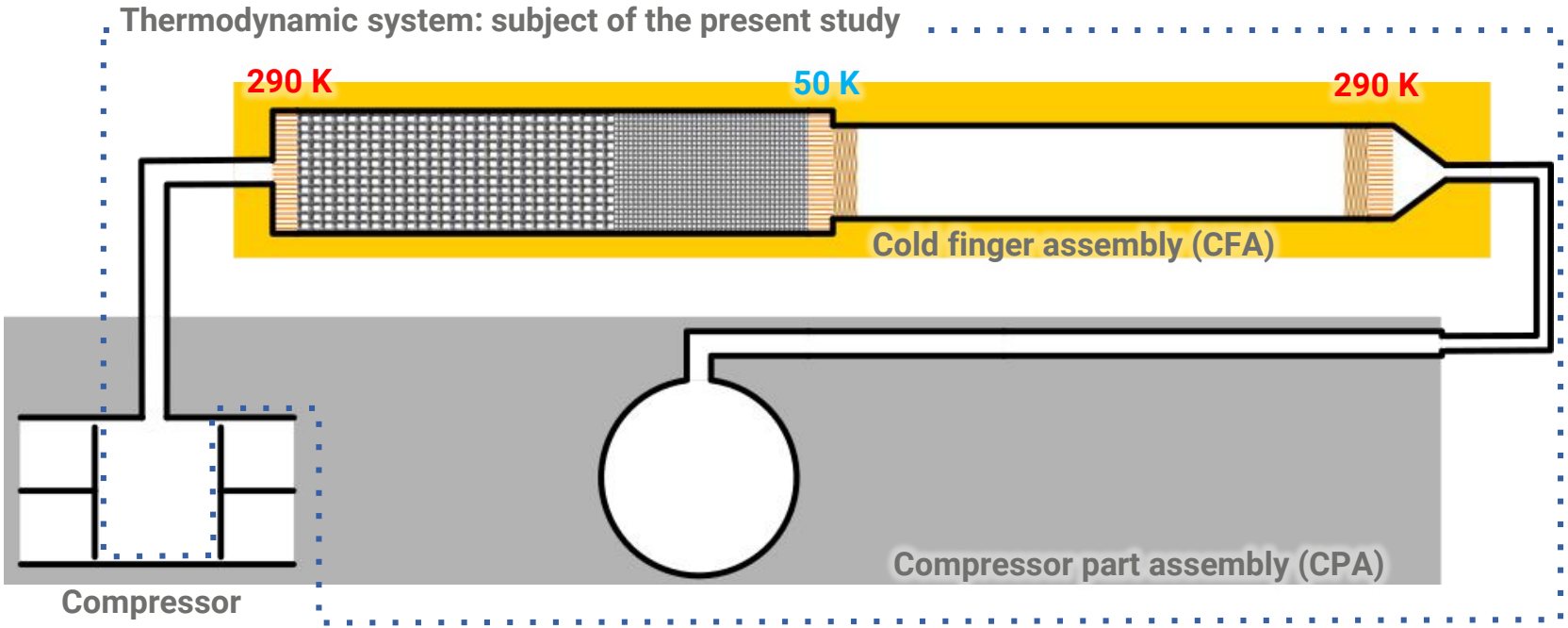
- Resonance
- Attenuation

→ **Vibrations**

2

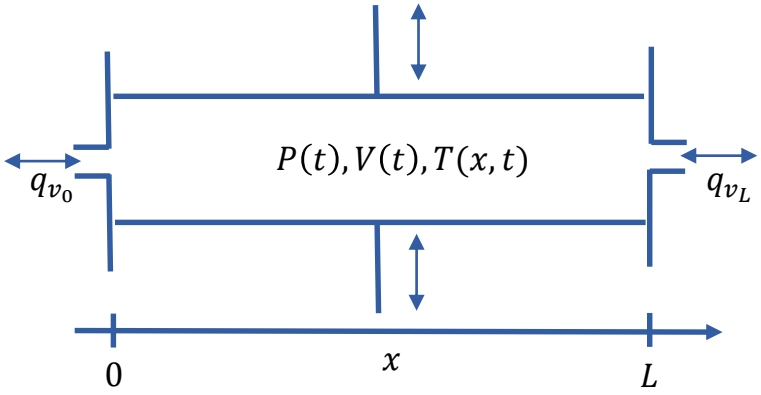
How to model fluid-mechanical behavior of a pulse tube cryocooler?

Modelling
Methodology



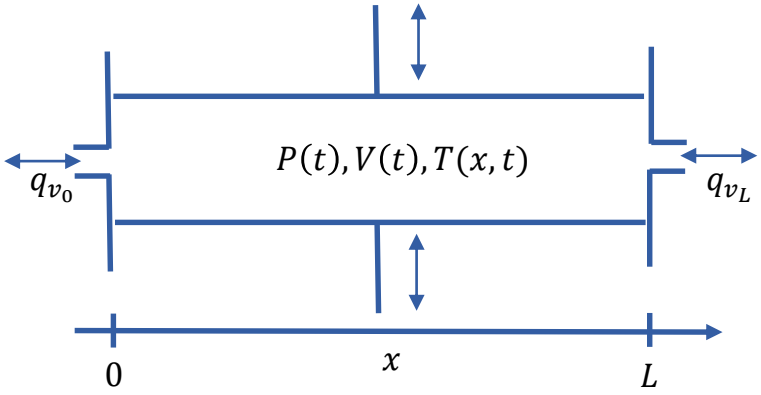
Modelling

Subsystem: volumes

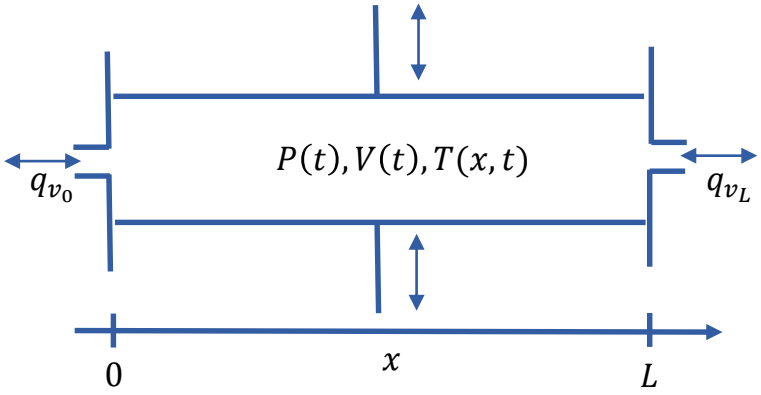


Modelling
Subsystem: volumes

Adiabatic Euler equations



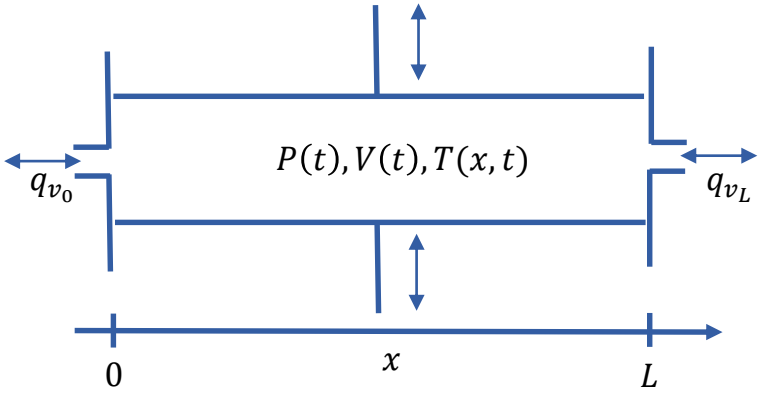
Modelling
Subsystem: volumes



Adiabatic Euler equations

$$\partial_t \ln(PS) + \gamma \partial_x v = 0$$

Modelling
Subsystem: volumes



Adiabatic Euler equations

$$\partial_t \ln(PS) + \gamma \partial_x v = 0$$

Integrations

$$P(t) = P(0)\left(\frac{V(0)}{V(t)}\right)^{\gamma} \exp\left(\gamma \int_0^t \frac{q_{v_0} - q_{v_L}}{V(t)} dt\right)$$

Modelling
Subsystem: lines

Adiabatic Euler equations

Modelling
Subsystem: lines

Adiabatic Euler equations

Simplifications and diagonalization

$$\begin{pmatrix} R_1 \\ R_2 \end{pmatrix}_t + \begin{pmatrix} c & 0 \\ 0 & -c \end{pmatrix} \begin{pmatrix} R_1 \\ R_2 \end{pmatrix}_x + \frac{\psi v|v|}{2\mathrm{d_h}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = 0 \qquad \text{with:} \qquad \begin{pmatrix} R_1 \\ R_2 \end{pmatrix} = \begin{pmatrix} v + \int \frac{c}{\rho} d\rho \\ v - \int \frac{c}{\rho} d\rho \end{pmatrix}$$

Modelling
Subsystem: lines

Adiabatic Euler equations

$$\begin{cases} R_1(x, t+\Delta t) = R_1(x-\Delta x, t) - \Delta t \dfrac{\psi v|v|}{2\mathrm{d_h}} \\ R_2(x, t+\Delta t) = R_2(x+\Delta x, t) - \Delta t \dfrac{\psi v|v|}{2\mathrm{d_h}} \end{cases}$$

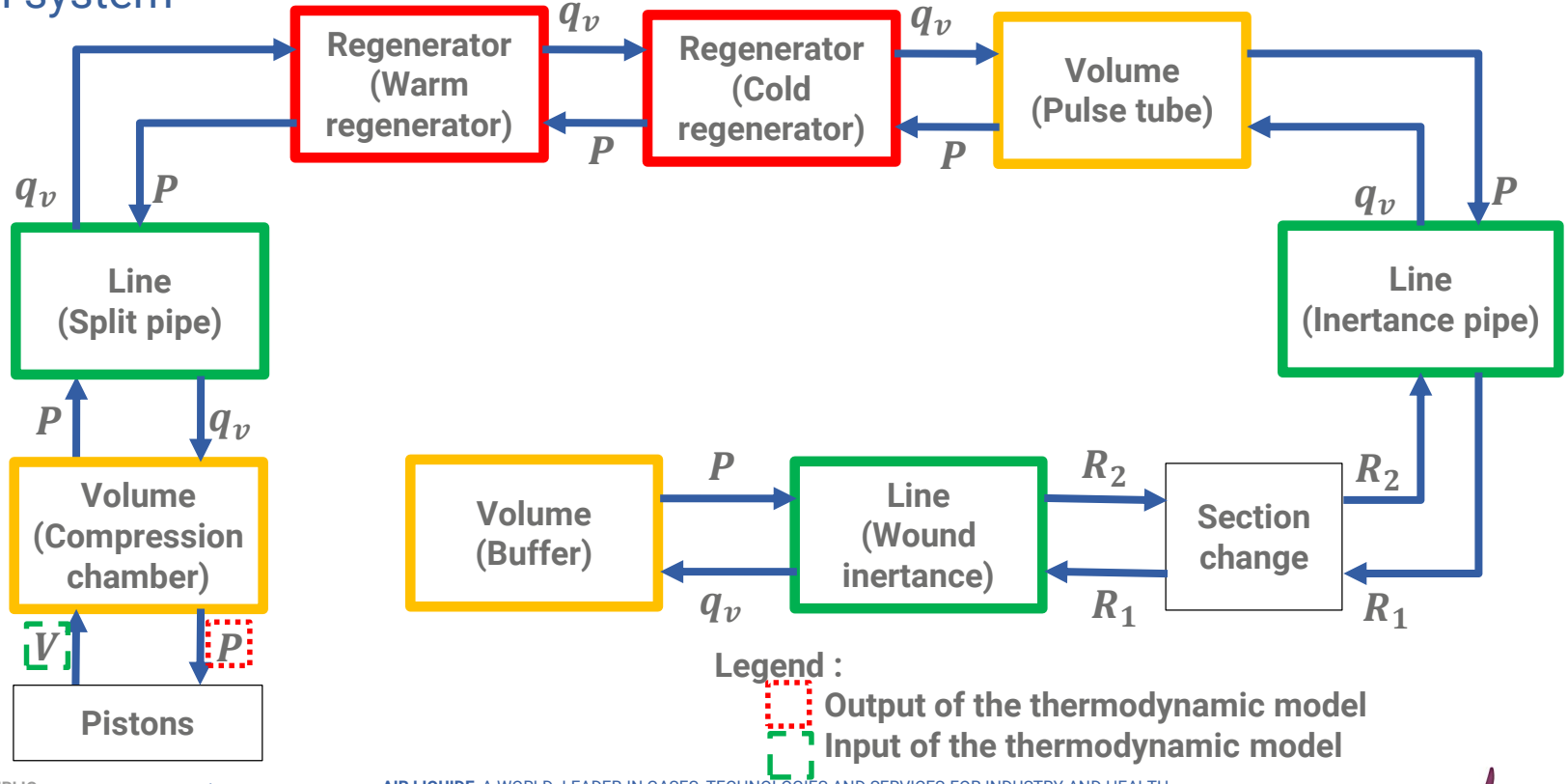
Simplifications and diagonalization

Directional derivative and discretisation

$$\begin{pmatrix} R_1 \\ R_2 \end{pmatrix}_t + \begin{pmatrix} c & 0 \\ 0 & -c \end{pmatrix} \begin{pmatrix} R_1 \\ R_2 \end{pmatrix}_x + \frac{\psi v|v|}{2\mathrm{d_h}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = 0 \qquad \text{with:} \qquad \begin{pmatrix} R_1 \\ R_2 \end{pmatrix} = \begin{pmatrix} v + \int \frac{c}{\rho} d\rho \\ v - \int \frac{c}{\rho} d\rho \end{pmatrix}$$

Modelling

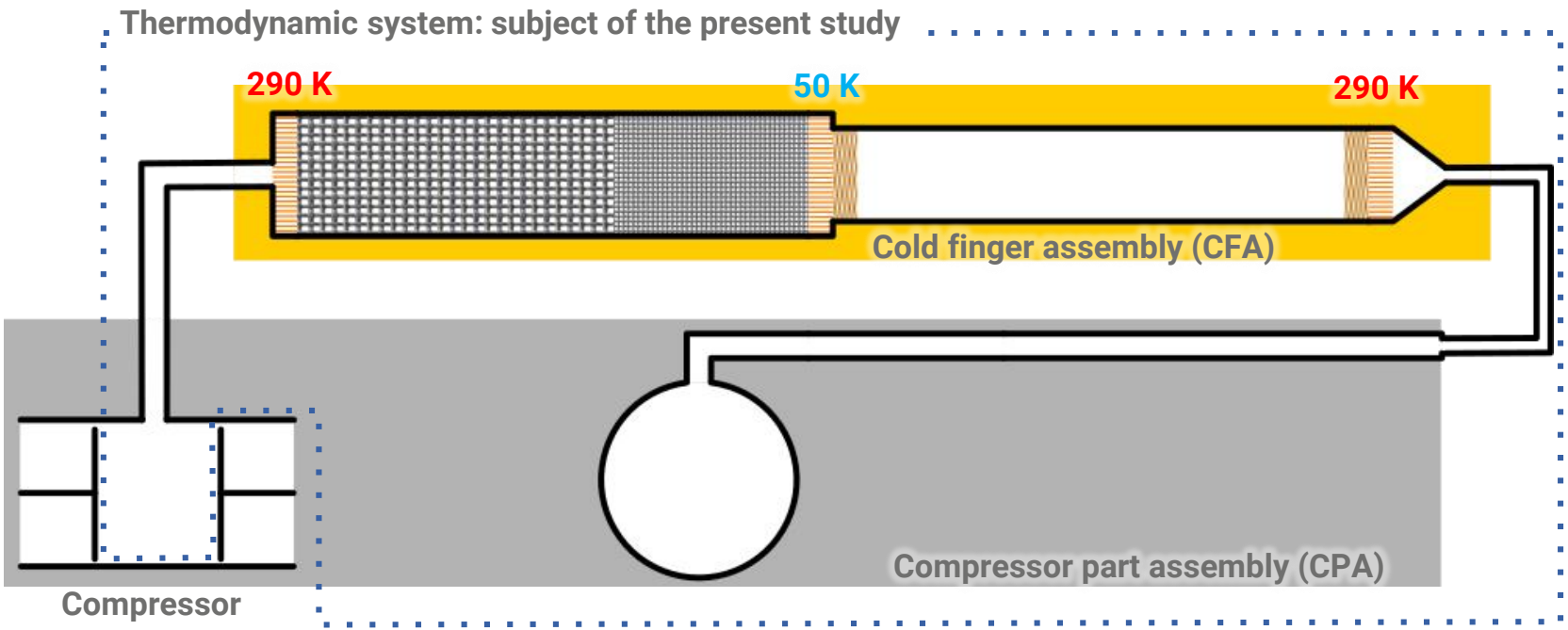
Overall system



3
Validation

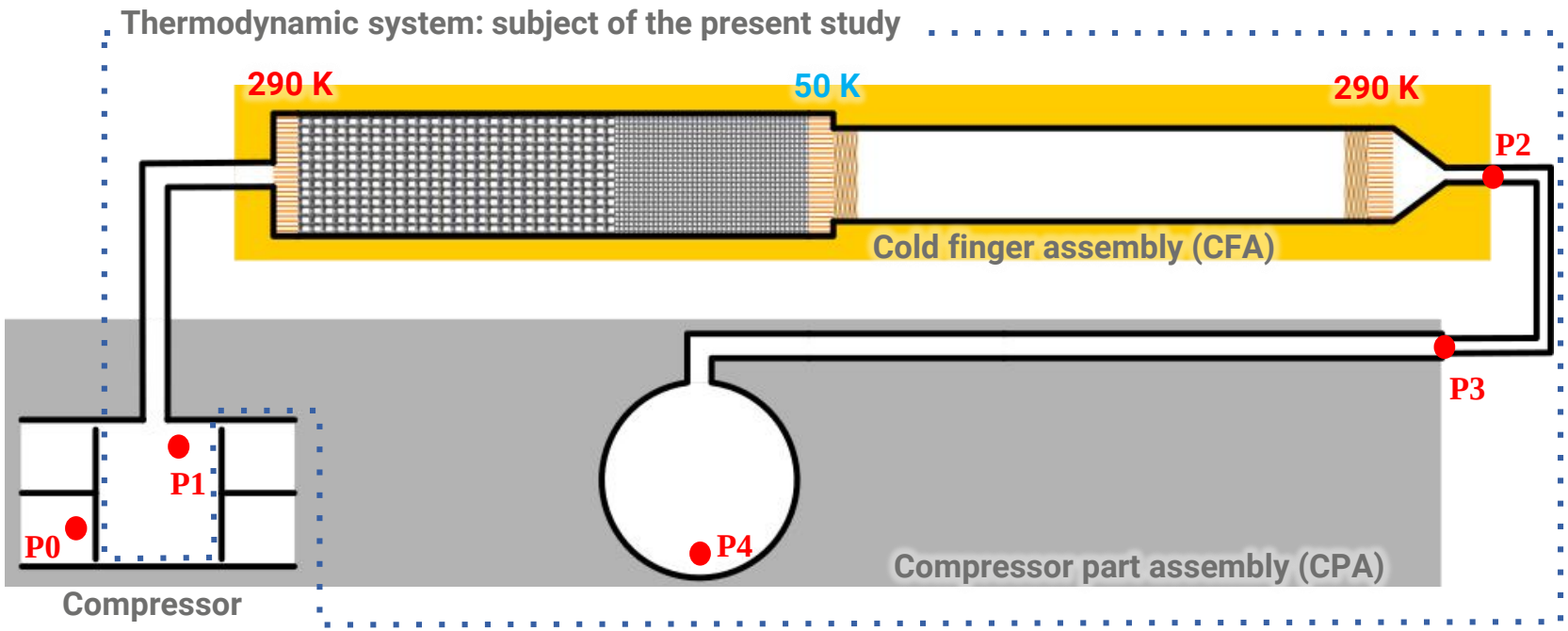
Experimental validation

Measurement points



Experimental validation

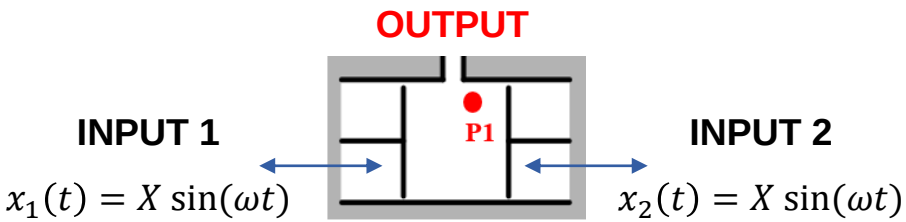
Measurement points

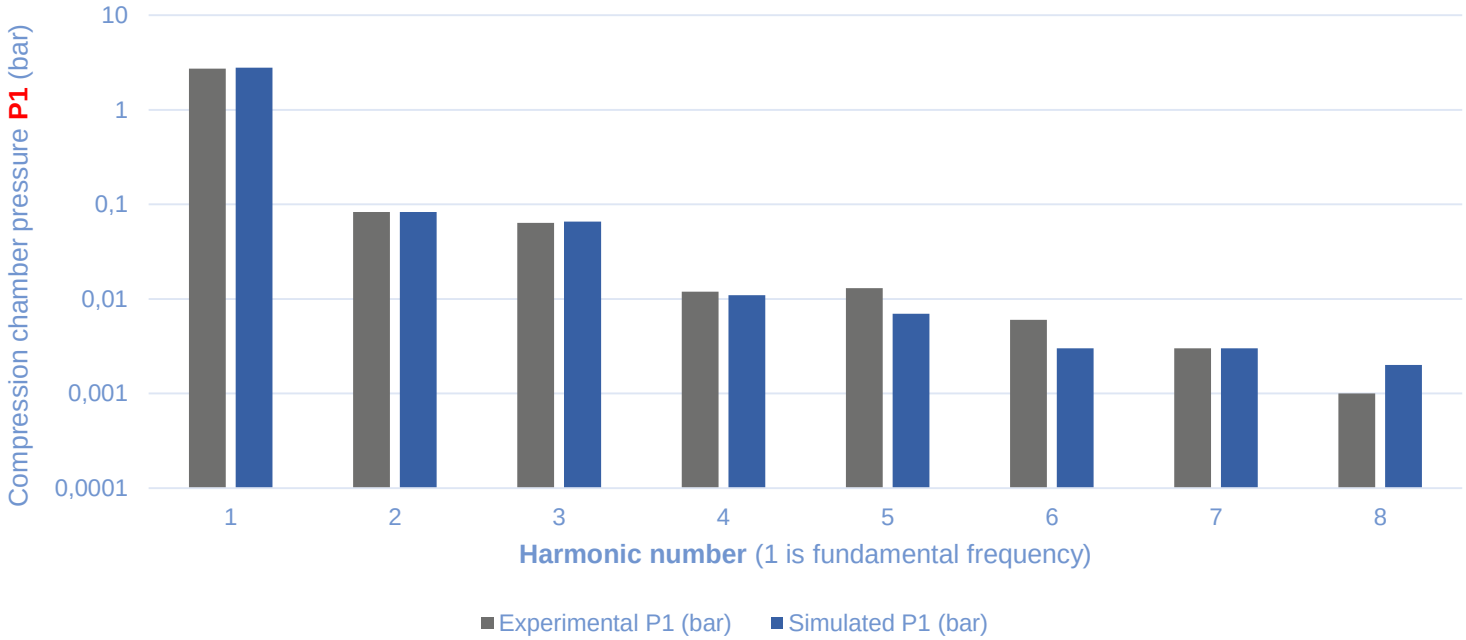


P# Test bench pressure measurements

Experimental validation

Comparison simulation/experiment

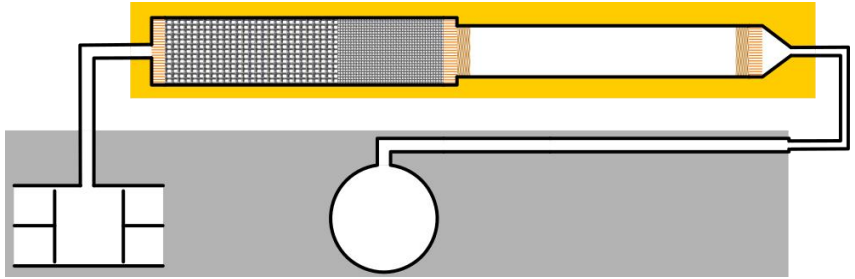




4

Conclusion and Prospects

Conclusion



Results:

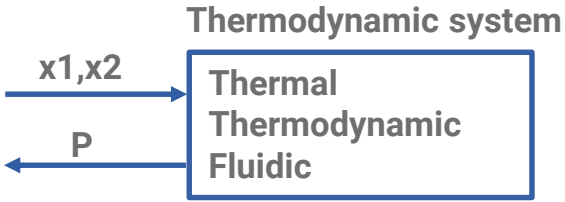
- **Highlighting of non-linear mechanical behavior of the thermodynamic system**
- **Simulated pressure harmonics very close to experimental ones**
- **Very efficient modeling of most components**

Considered improvements:

- **Method of characteristics applied to regenerators → significant time step reduction**
- **Better calibration of the sensors to reduce uncertainties**

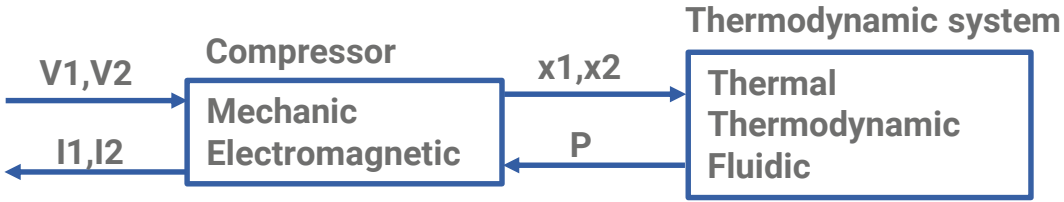
Prospects

- **Calculation of vibrations due to fluid-structure interactions**
- **Integration to a whole cryocooler model**



Prospects

- **Calculation of vibrations due to fluid-structure interactions**
- **Integration to a whole cryocooler model**



Power consumption

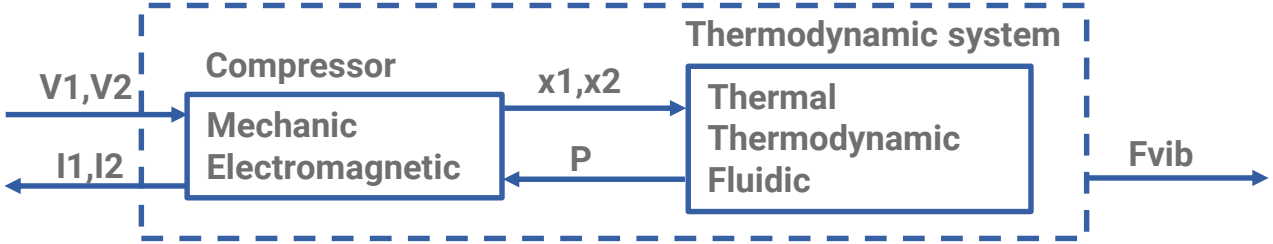
Prediction

Electrical harmonics

Understanding
Prediction

Prospects

- **Calculation of vibrations due to fluid-structure interactions**
- **Integration to a whole cryocooler model**



Power consumption

Prediction

Electrical harmonics

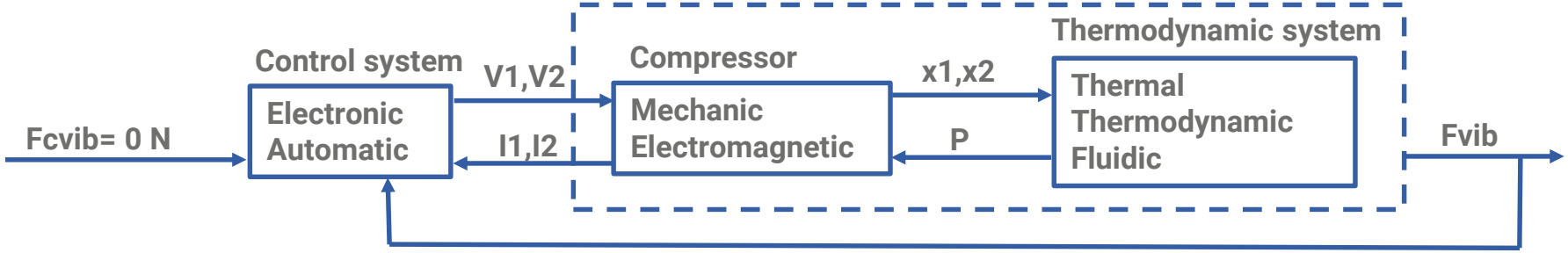
Understanding
Prediction

Vibrations

Understanding
Prediction

Prospects

- **Calculation of vibrations due to fluid-structure interactions**
- **Integration to a whole cryocooler model**



Power consumption

Prediction

Electrical harmonics

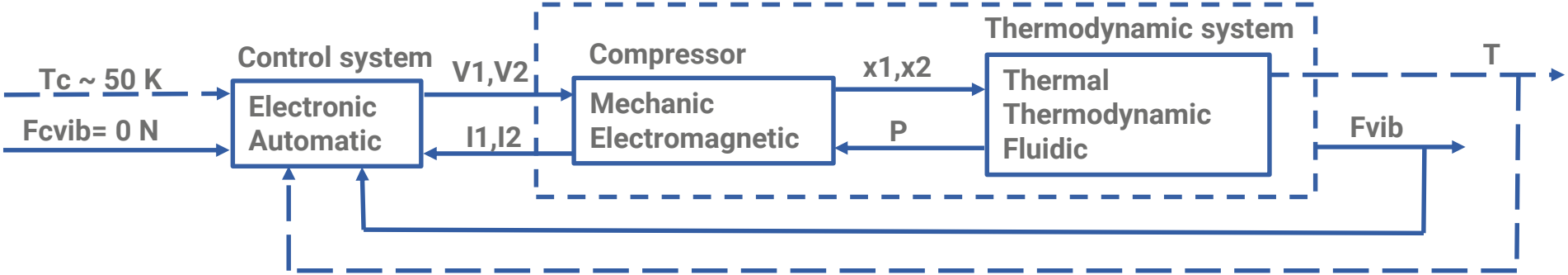
Understanding
Prediction

Vibrations

Understanding
Prediction
Reduction

Prospects

- **Calculation of vibrations due to fluid-structure interactions**
- **Integration to a whole cryocooler model**



Power consumption

Prediction

Electrical harmonics

Understanding
Prediction

Vibrations

Understanding
Prediction
Reduction

Modelling

Subsystem: Regenerators

Euler equations with isothermal relashionship:

$$\begin{cases} \partial_t(\rho S) = -\partial_x(\rho v S) \\ \partial_t(\rho v S) = -\partial_x(\rho v^2 S) - \partial_x(PS) - \dfrac{\psi S \rho v |v|}{2 d_h} \\ \partial_t\left(\dfrac{P}{\rho}\right) = 0 \end{cases}$$

Simplifications and discretisation

$$\begin{cases} \rho(x, t+\Delta t) = \rho(x,t) - \Delta t \dfrac{\rho(x+\Delta x, t) v(x+\Delta x, t) - \rho(x-\Delta x, t) v(x-\Delta x, t)}{2\Delta x} \\ v(x, t+\Delta t) = v(x,t) - \Delta t \left(v(x,t) \dfrac{v(x+\Delta x, t) - v(x-\Delta x, t)}{2\Delta x} + \dfrac{1}{\rho(x,t)} \dfrac{P(x+\Delta x, t) - P(x-\Delta x, t)}{2\Delta x} + \dfrac{\psi v(x,t)|v(x,t)|}{2 d_h} \right) \\ P(x, t+\Delta t) = P(x,t) \dfrac{\rho(x, t+\Delta t)}{\rho(x,t)} \end{cases}$$