# The influence of a heat exchanger on a water hammer

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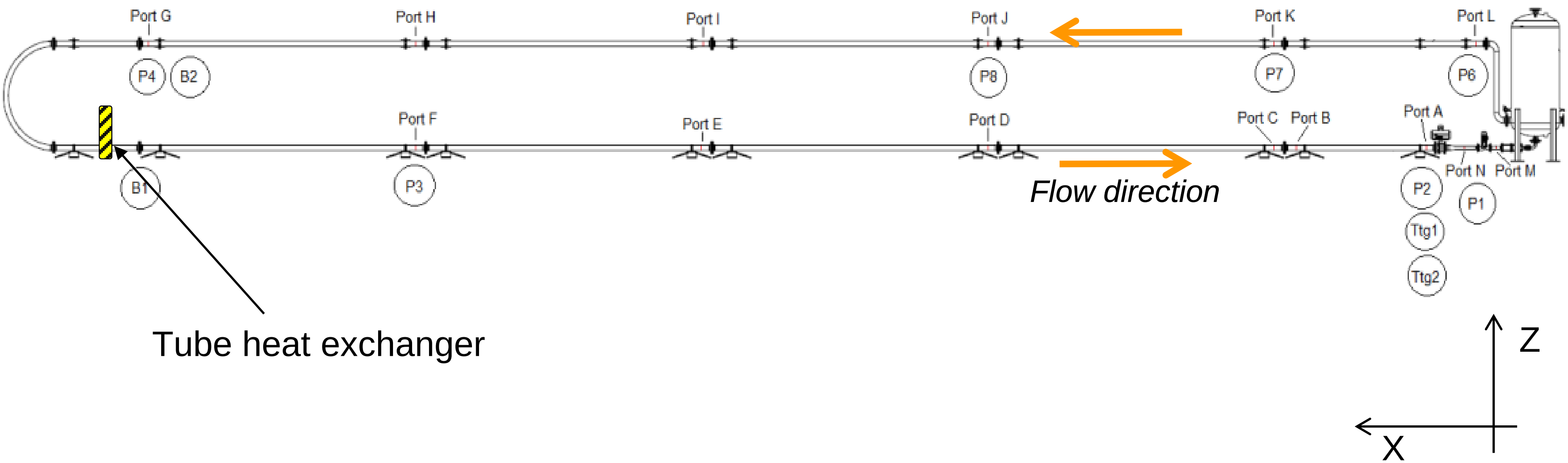
R&D Business Strategy
Research & Development
R&D Laboratories
Vattenfall AB

Confidentiality - None (C1)

# Background

- Heat exchangers are not modelled in pipe system load calculations at NPPs
- There is a consensus that loads are damped by heat exchangers
- Aim:
  - Build a test rig and perform an experiment of a water hammer with a heat exchanger
  - Construction and validation of a heat exchanger model in Relap5

# Test rig and instrumentation



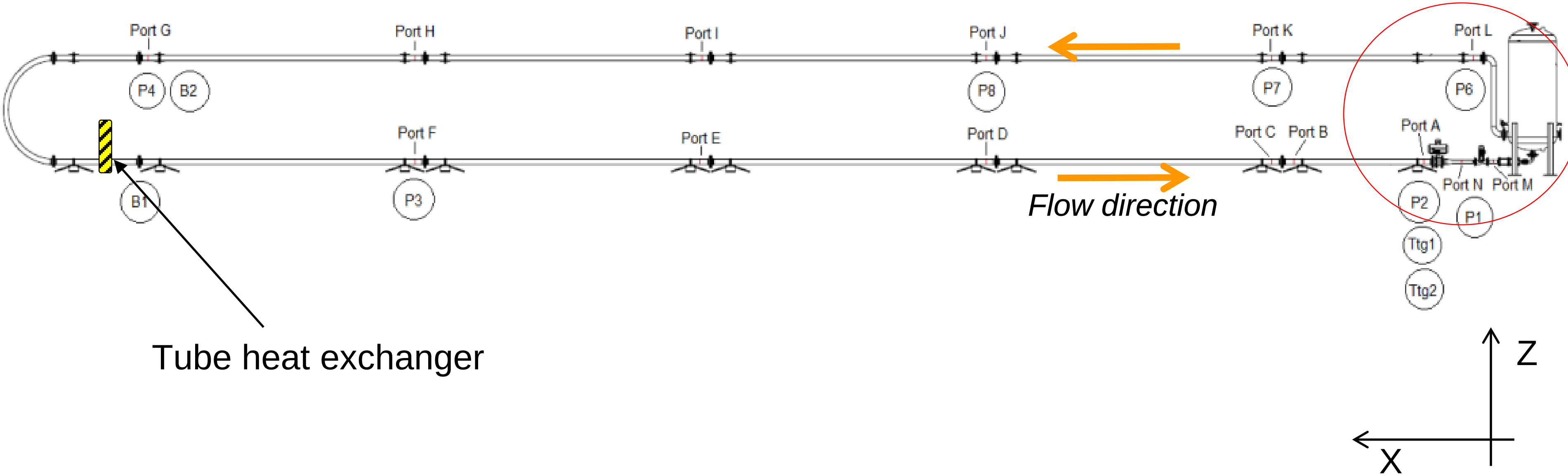

<u>Test rig</u>

- L=63 m
- 180°, R=10 D= 1 m
- DN100, t=3 mm
- PN25 (tank limitation)
- Tap water (removed hard minerals)
- T=20°C

<u>Instrumentation</u>

- P: pressure sensors (180 kHz, ε=0.25 %)
- Ttg = strain gauge

# Test rig and instrumentation

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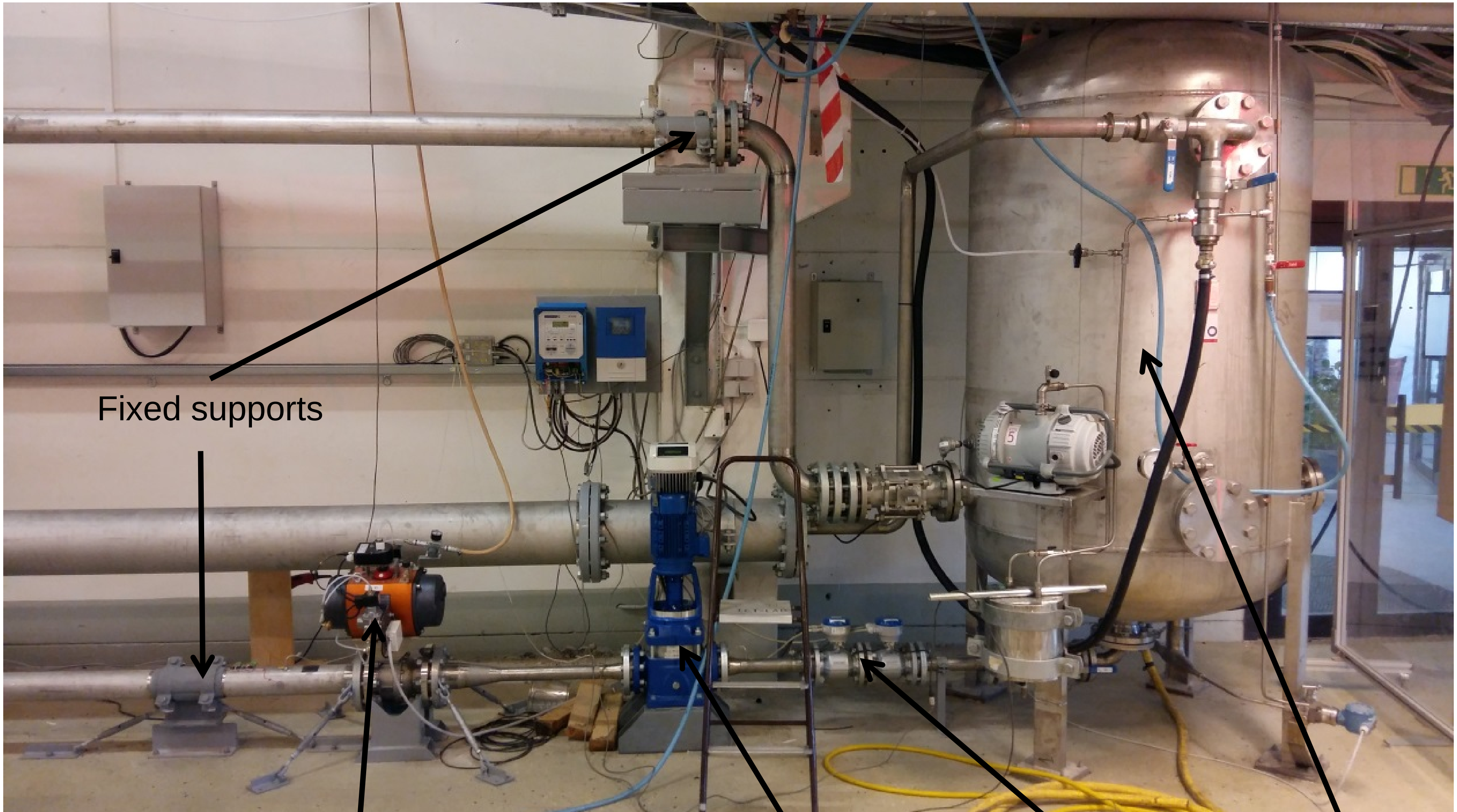
# Water Hammer Test rig components



Fixed supports

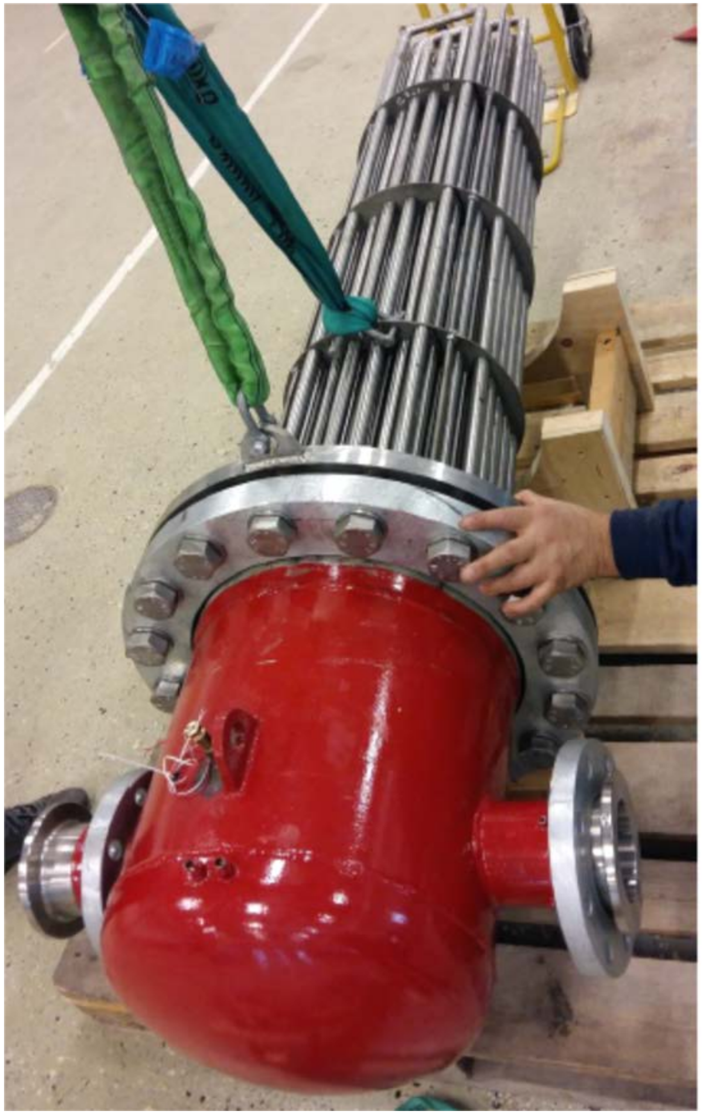
Fast-closing (30 ms) ball-valve (spring-driven)

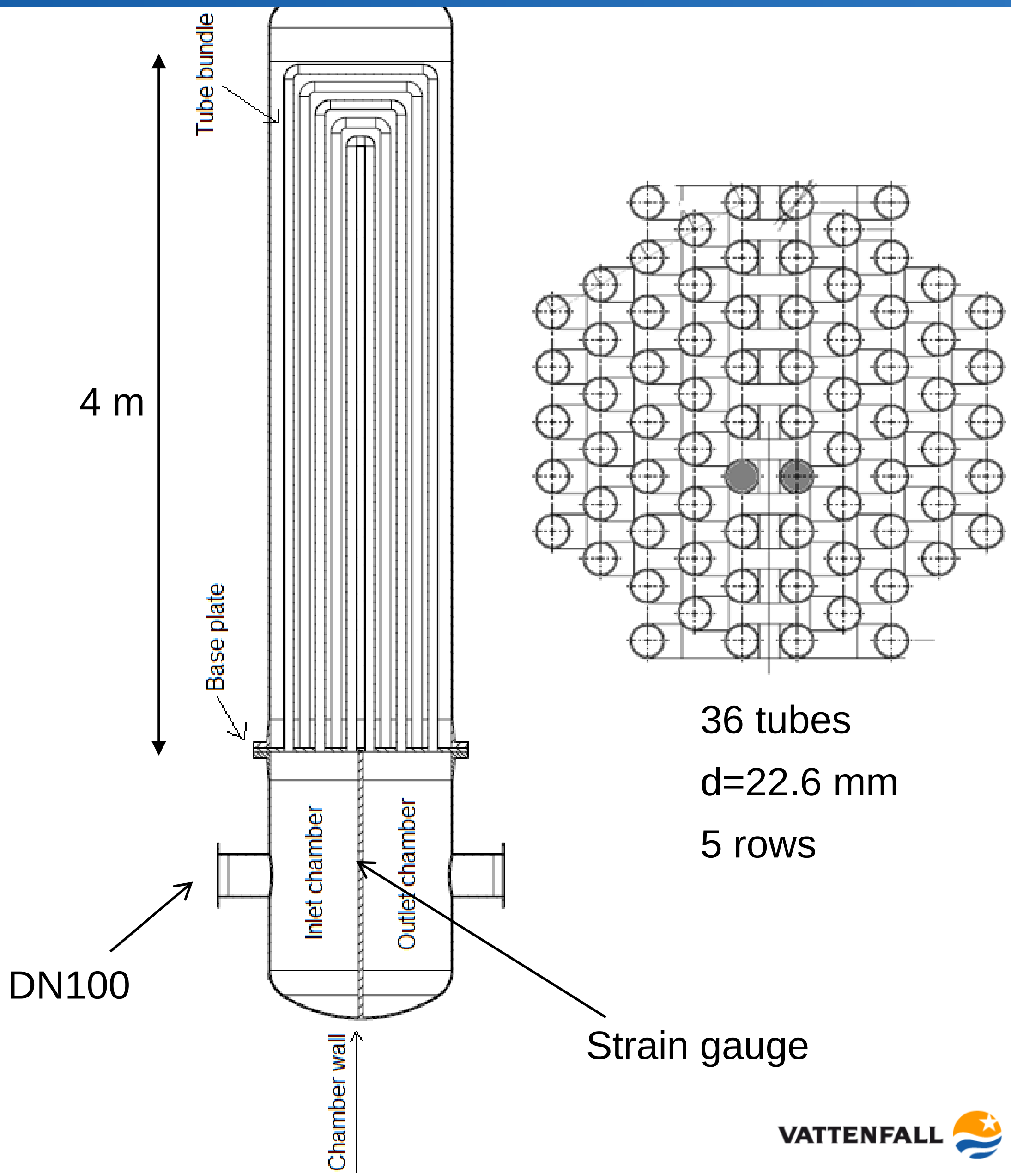
Pump

Flow meters

$N_2$-pressurized tank

# Tube heat exchanger






36 tubes

d=22.6 mm

5 rows



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# Test cases

36 open tubes

13 open tubes

5 open tubes



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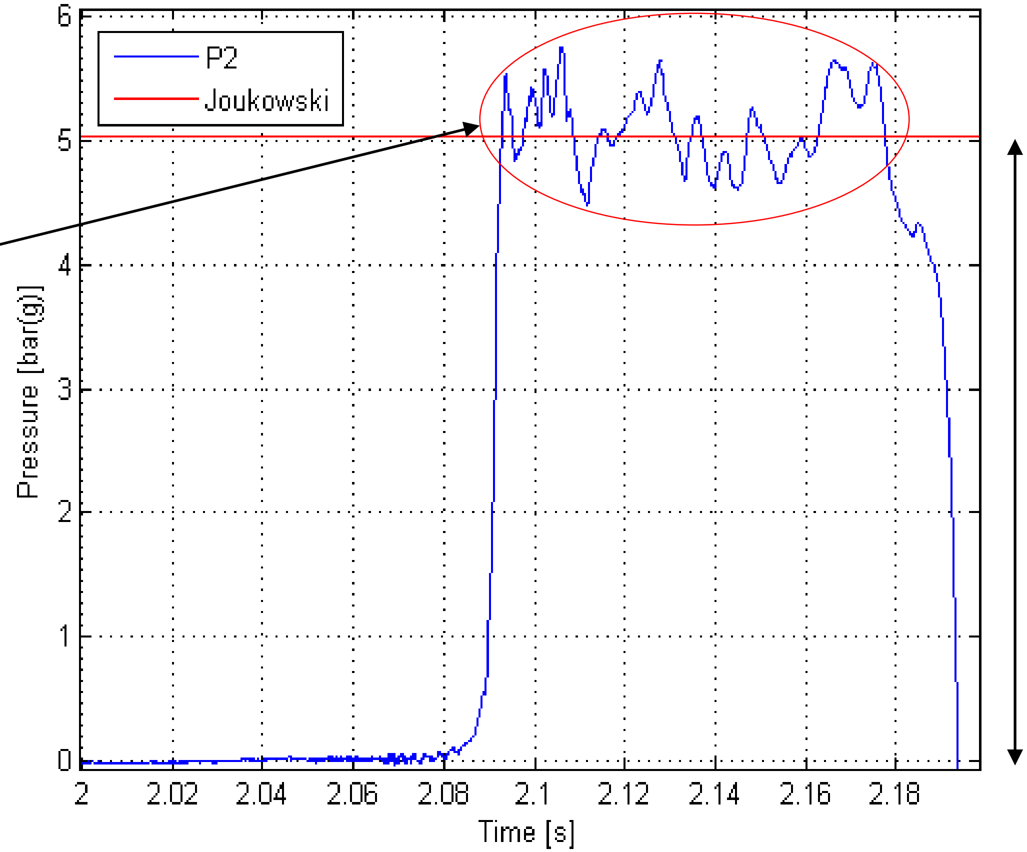
# Water hammer

Violent valve closure

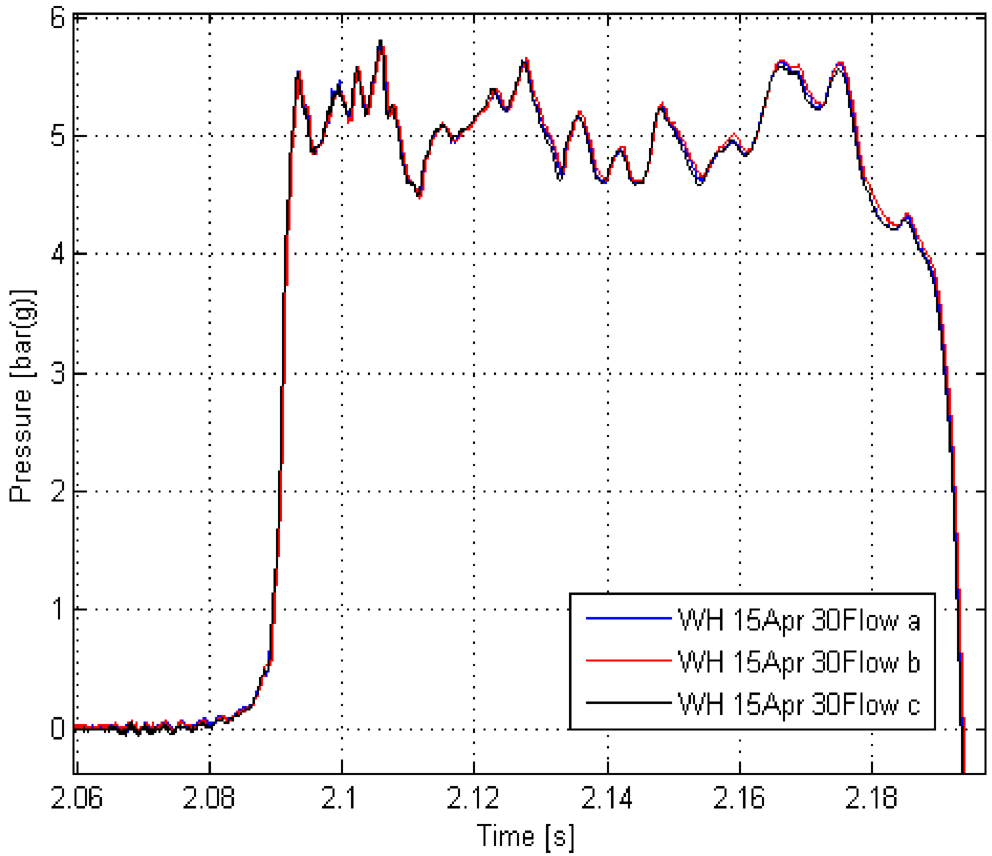



Joukowski:

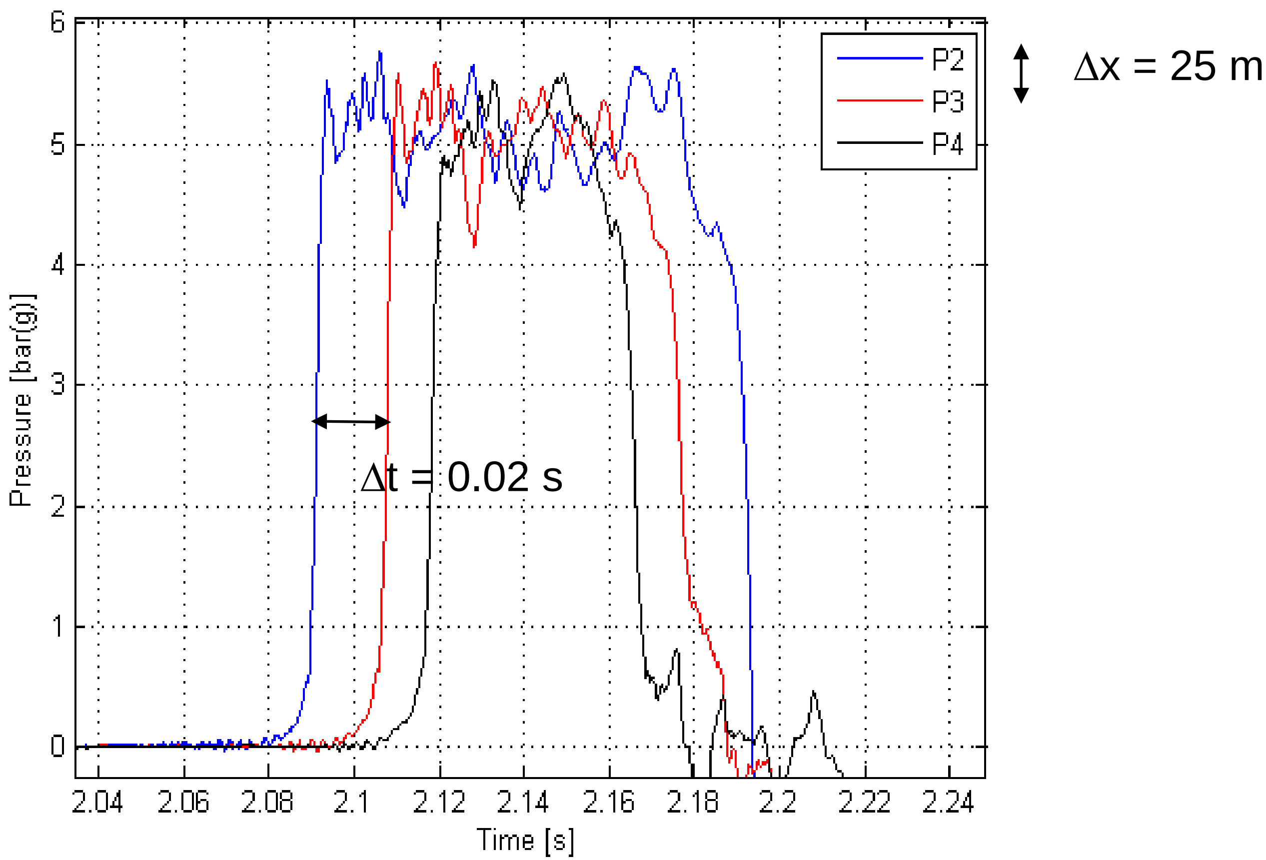
$$\Delta p = \rho\, c\, \Delta v$$

- $\Delta p$: pressure increase [Pa]
- $\rho$: fluid density [kg/m$^3$]
- c: speed of sound or pressure wave propagation speed [m/s]
- $\Delta v$: fluid velocity change from v=Q/A to 0 [m/s]

# Repeatability

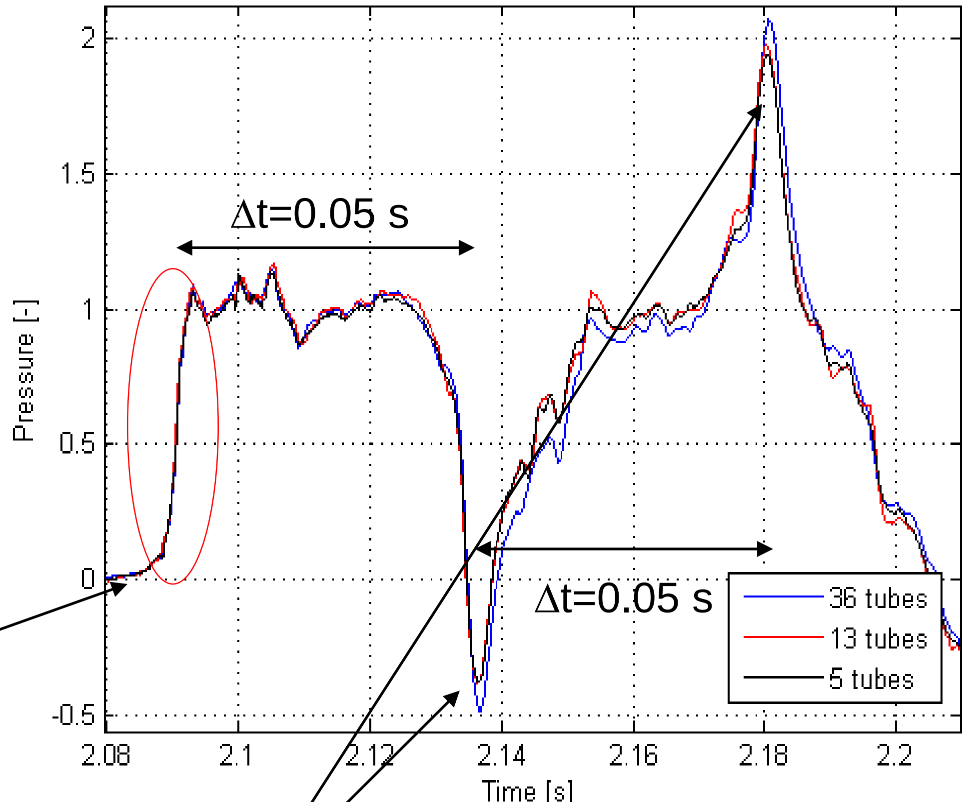


# Pressure wave propagation speed




Pressure wave propagation speed: c=Δx/Δt=25 m/0.02 s=1245 m/s

# Pressure wave propagation: P2 normalized $\Delta p = \rho\, c\, \Delta v$




Valve closure

1st and 2nd reflexion in the heat exchanger



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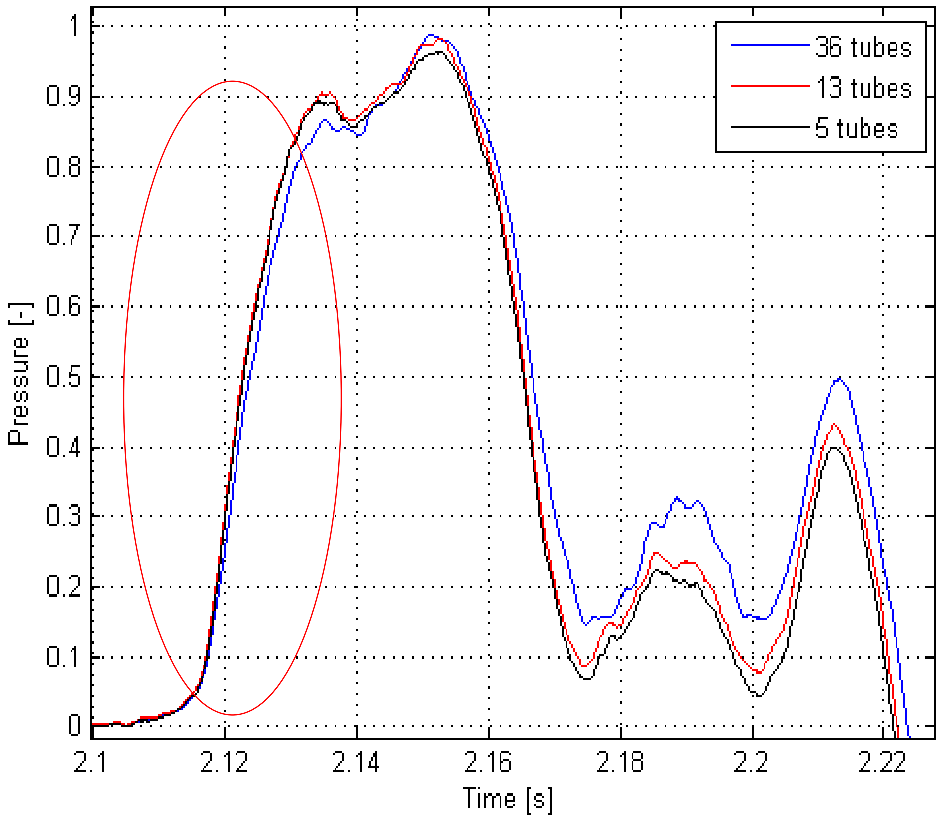
# Pressure wave propagation: P4 normalized $\Delta p = \rho c \Delta v$




F~∂p/∂t decreases after the heat exchanger



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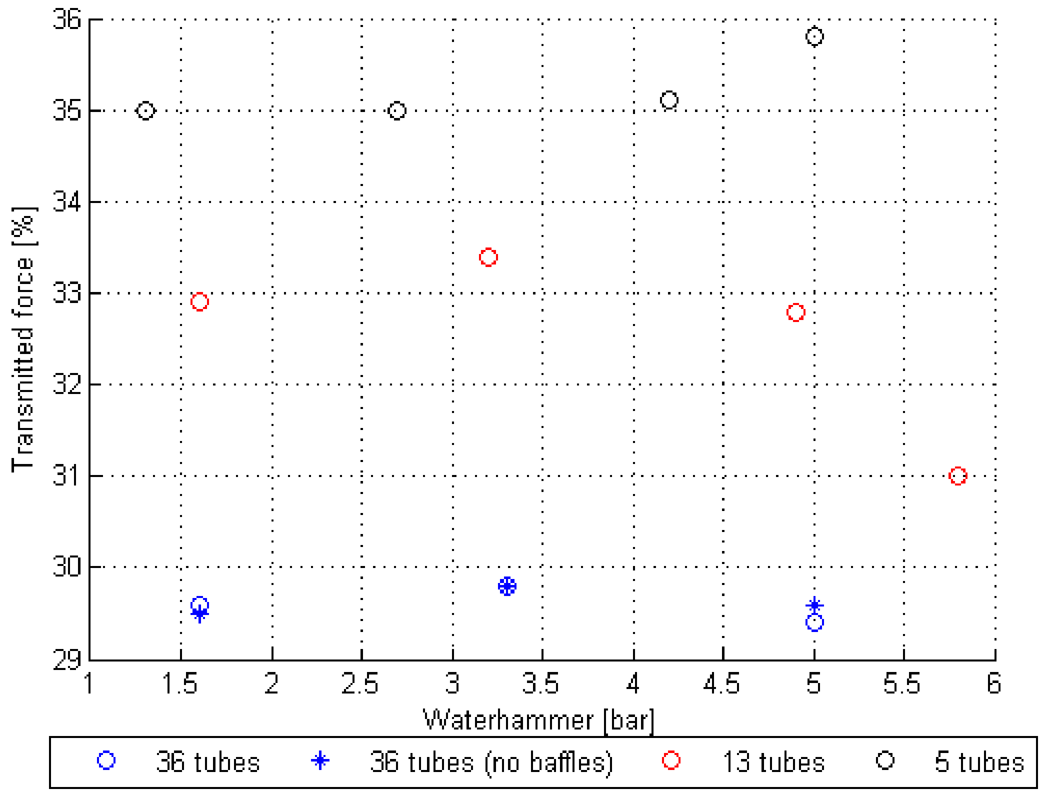
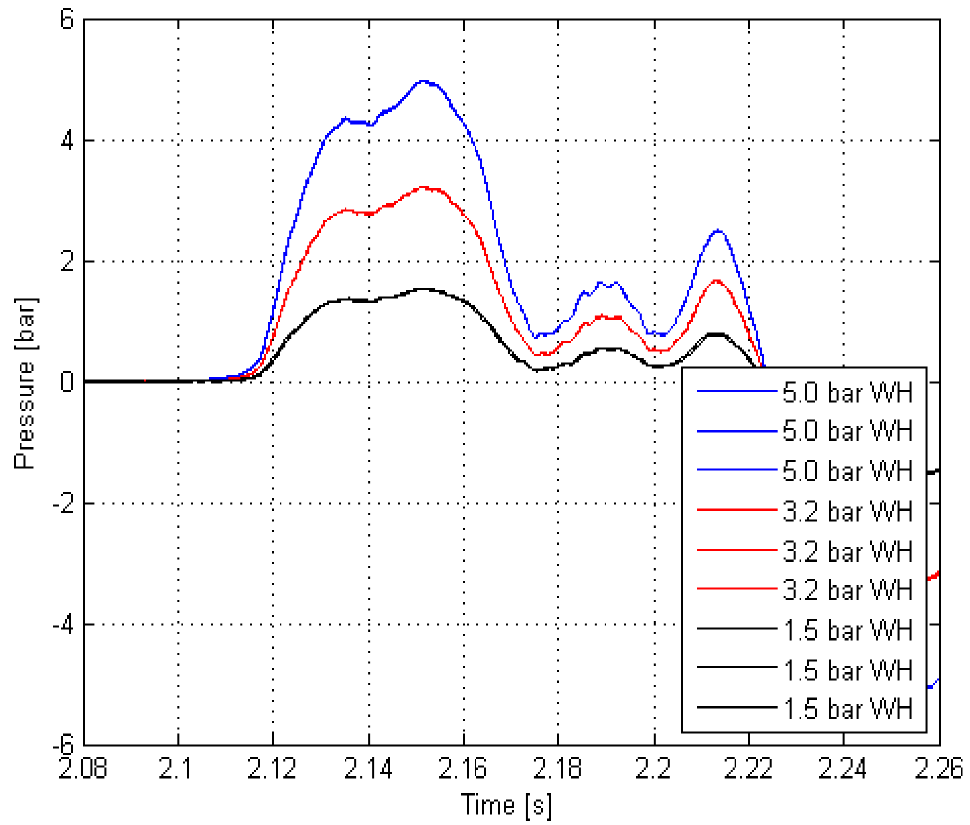
# Heat exchanger effect on transmitted load

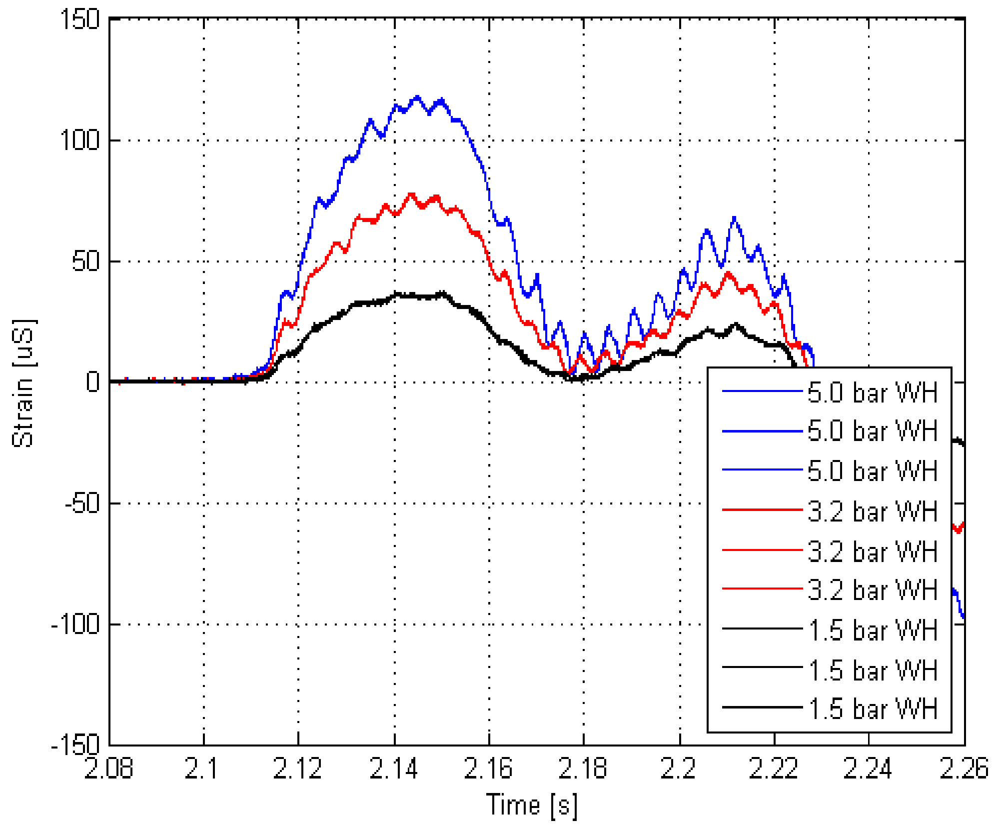



The transmitted load (~1/3) increases slightly with decreasing number of tubes

# P4, 36 tubes, varied Δ*v*



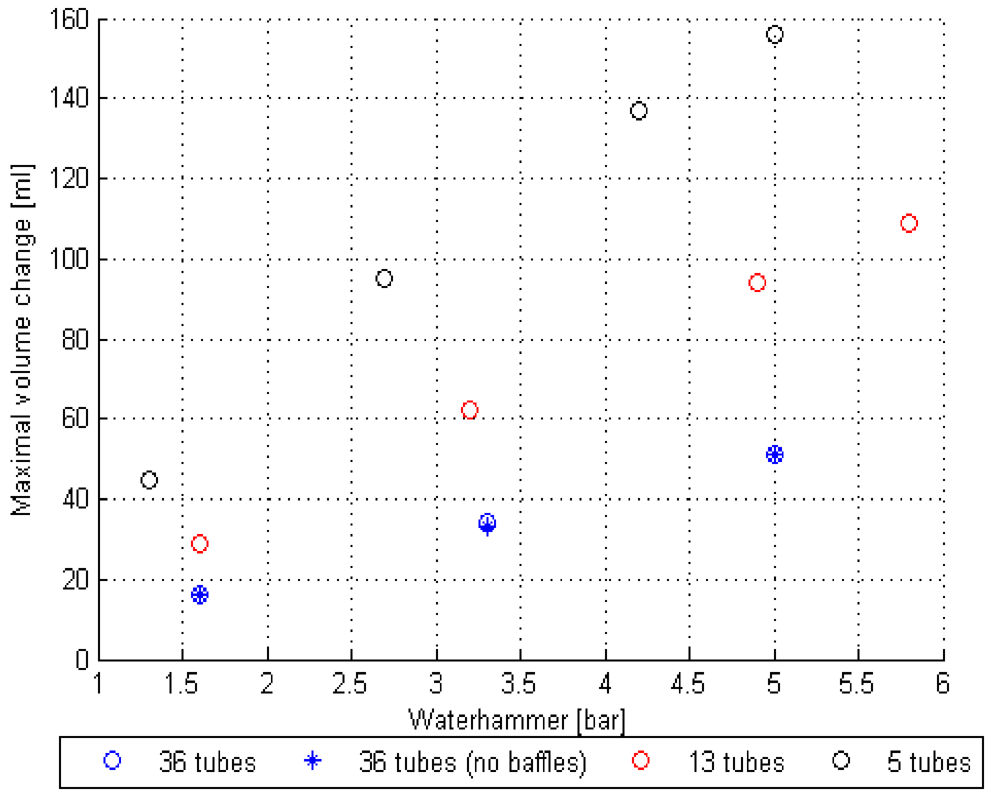
# Axial strain: chamber divider wall, 36 tubes, varied $\Delta v$




Fluid Structure Interaction (FSI):

Heat exchanger chamber wall is deflected by the transient pressure difference

# Fluid Structure Interaction: heat exchanger chamber wall




The FSI-effect increases with decreasing number of tubes

# Conclusions experimental tests

- Investigations of the effect of a heat exchanger on the water hammer.

- The test rig performs well and the data has good accuracy and repeatability.

- The purpose of these tests is to generate data for validation of a RELAP5 model.

Results:

- The heat exchanger smoothens out the pressure transient and reduces the loads.

    - This is due to the area changes in the heat exchanger and the FSI-effect of the chamber wall.

# Water hammer analysis
## Complex components

# RELAP5

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# RELAP5

- RELAP5 can handle only pure fluid calculations and it is impossible to take into account the interaction with structural components
- $c_{fp} = c\sqrt{\frac{1}{1+DB/Et}}$ ,

*B:* bulk modulus of the fluid,

*E:* Young's modulus of the pipe,

*D:* diameter of the pipe,

*t:* thickness of the pipe

- The different speed of sound in the fluid-and-pipe can be handled in RELAP5 with a post process with the right scaling of the time
- The pressure wave predicted by RELAP5 is, generally, stronger than the real one that is generated in the system because of the difference in the Joukowsky pressure as consequence of different sound speed



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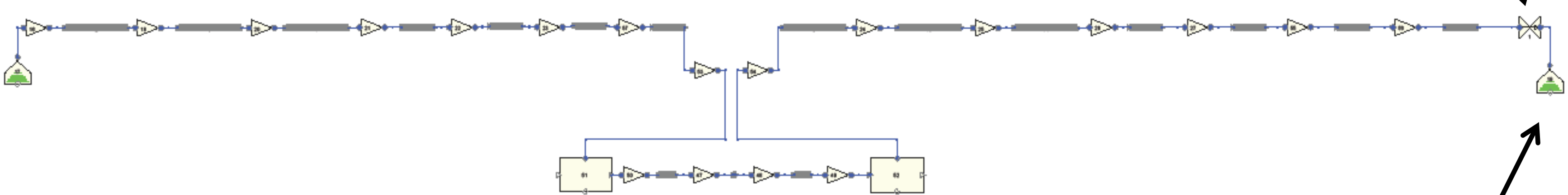
# RELAP5 Modelling

Time Dependent Volume with a constant temperature (293.15 K) and pressure calibrated to have the desired mass flow rate

30 meters long pipe with inner diameter 0.1 m, nodalization L/D=1

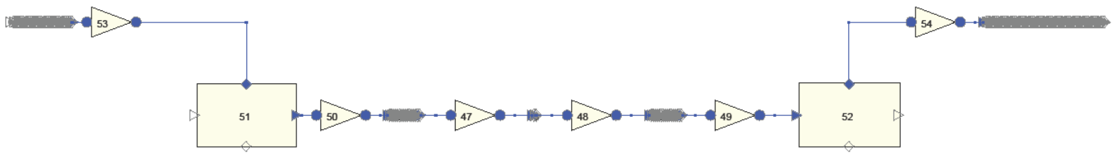
valve



heat exchanger section

Time Dependent Junction with a constant temperature (293.15 K) and pressure (10e6 Pa)

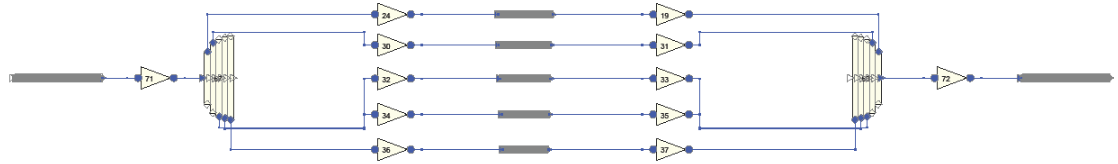
# RELAP5 tube heat exchanger: Simple model




The Headers are modelled with a single horizontal volume. The chosen geometrical parameters are the total volume, the area and the hydraulic diameter in the X direction, the length in the Y direction

The tubes are modelled with three in-line pipe components using the same equivalent length, total area and equivalent diameter as the tubes in the experimental setup

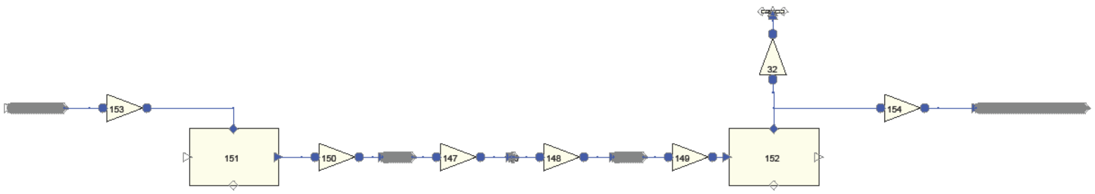
# RELAP5 tube heat exchanger: Detailed model




The Headers are modelled with a horizontal pipe component divided into 5 nodes, each 0.04 m in length. The chosen geometrical parameters are the total volume and the length in the X direction which corresponds to the distance between the inlet of the pipe and the division plate, 0.2 m. The volume of each node has been calculated with geometrical considerations.

The number of nodes in the Headers has been chosen based on the number of Tubes. The Tubes have been divided into 5 parallel groups modelled with pipe components in agreement with the geometry of the 5 rows of the experimental heat exchanger. Each Tube is modelled using the equivalent length, the total area and the equivalent diameter of the tubes in the experimental setup.

# RELAP5 tube heat exchanger: Bubble model




A single vertical volume, containing Nitrogen at 293.15 K and 10e6 Pa, is added and coupled to the exit Header of the heat exchanger through a Single Junction.

The bubble volume is used in order to simulate the effects of the compressibility-deformation of the metal structure. The pressure wave creates a variation of the volume in the Headers, mainly because of the deformation of the plate divisor (positioned between the headers).



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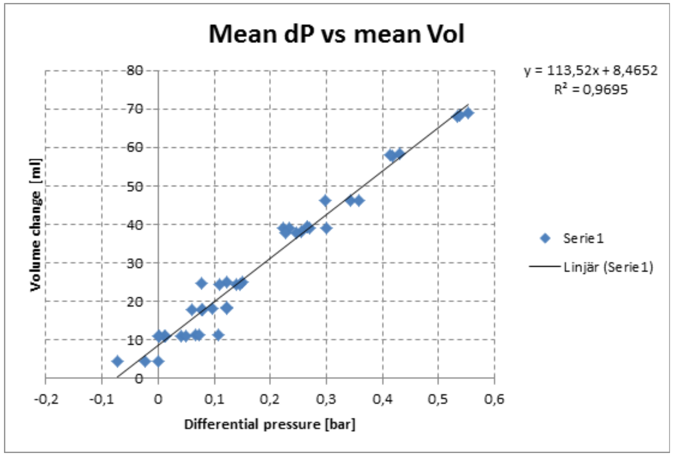
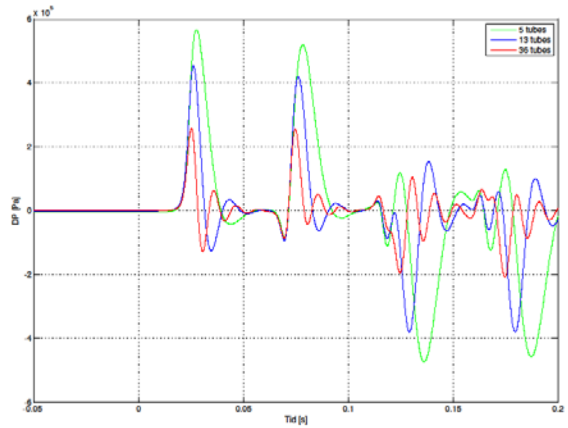
# RELAP5 tube heat exchanger: Bubble model

Bubble Best Fit model: the bubble volume size is chosen in order to have the best fit of the "P2" experimental data, which is the pressure transducer positioned close to the valve. Run 10%, 20% and 30% correspond respectively to the 10, 20 and 30% of the maximum frequency of the pump (50Hz).

| | Bubble size [ml] | | |
|---|---|---|---|
| Run | 10% | 20% | 30% |
| 36tubes | 84 | 84 | 105 |
| 13tubes | 78.6 | 83.5 | 91 |
| 5tubes | 85 | 87.8 | 90 |

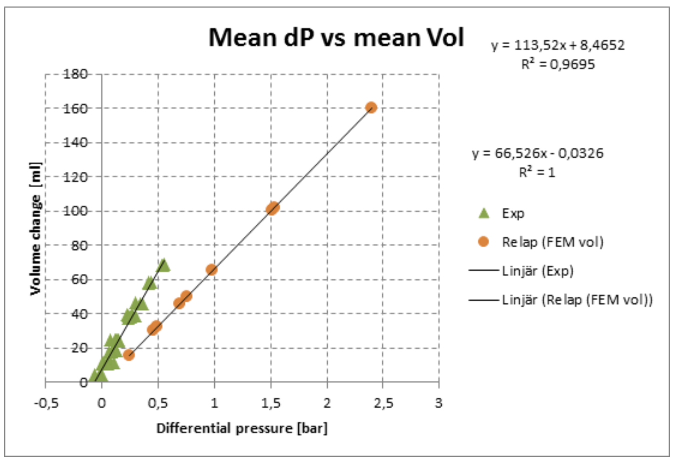
# RELAP5 tube heat exchanger: Bubble model

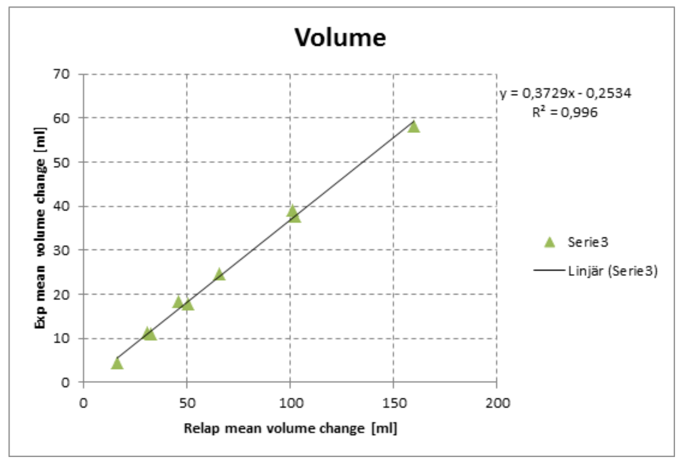



Bubble DP24 model

$$\bar{P} = \overline{(P_{in} - P_{out})}|_{1st\ peak}$$




$$\Delta V = 0.373 \cdot 66.5 \cdot \overline{P} = 24.8 \cdot \overline{P}$$

$$\Delta V = 24.8 \cdot \overline{P} = V_i - V_f = V_i \cdot \left(1 - \left(\frac{P_i}{P_{\max}}\right)^k\right)$$

| | Bubble size [ml] | | |
|---|---|---|---|
| Run | 10% | 20% | 30% |
| 36tubes | 50.46 | 54.5 | 59.87 |
| 13tubes | 106.03 | 111.19 | 133.84 |
| 5tubes | 190.82 | 212.66 | 237.5 |



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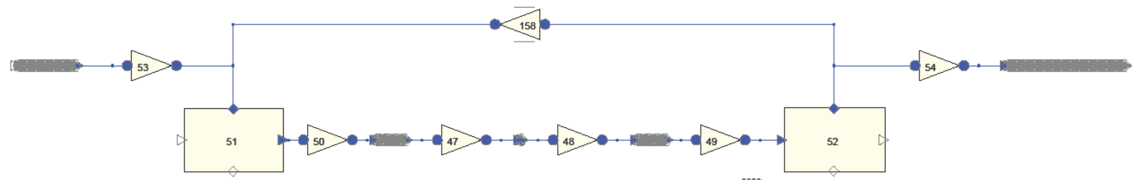
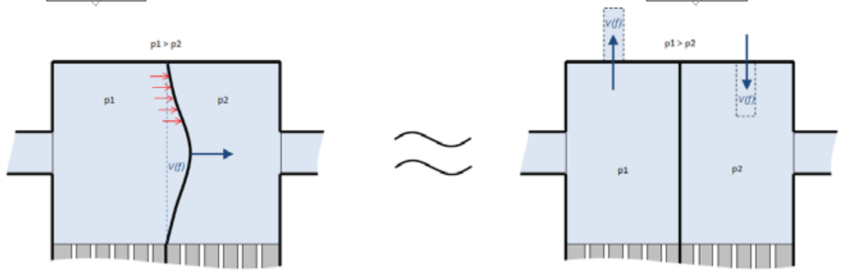
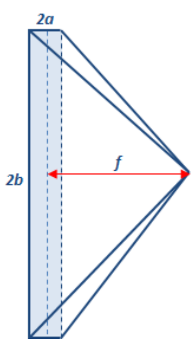
# RELAP5 tube heat exchanger: Time Dependent Junction model



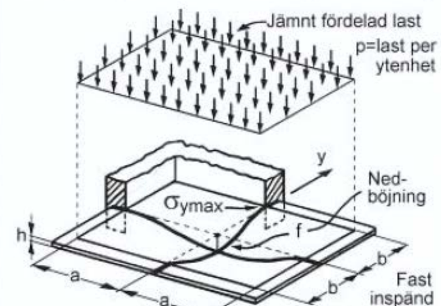




$$V = 2a \cdot 2b \cdot f/3$$

$$f = 0.35 \cdot \frac{\Delta p \cdot b^4}{E \cdot h^3} = \Delta p \cdot 2.24 \cdot 10^{-8}$$

**Spänningar och formändringar i fast inspänd rektangulär platta påverkad av en jämnt fördelad last**




Jämnt fördelad last p·2a·2b över rektangulär platta, fast inspänd längs alla fyra sidorna. Den största spänningen uppträder vid inspänningen mitt på den längre sidan 2a. Den går i y-riktning och betecknas $\sigma_{ymax}$

| Sidoförhållande | Nedböjning | Spänningar i plattans mitt | | |
|---|---|---|---|---|
| $\frac{2a}{2b}$ | $\frac{f}{\frac{pb^4}{Eh^3}}$ | $\frac{\sigma_x}{\frac{pb^2}{h^2}}$ | $\frac{\sigma_y}{\frac{pb^2}{h^2}}$ | $\frac{\sigma_{ymax}}{\frac{pb^2}{h^2}}$ |
| 1,0 | 0,225 | ±0,53 | ±0,53 | ±1,24 |
| 1,5 | 0,394 | ±0,48 | ±0,88 | ±1,82 |
| 2,0 | 0,431 | ±0,31 | ±0,94 | ±1,92 |
| ∞ | 0,455 | ±0,30 | ±1,00 | ±2,00 |

Krökningen vid inspänningen är den motsatta mot krökningen i mitten. Spänningarna vid inspänningen har då motsatta tecken jämfört med spänningarna i mitten. Vid inspänningen längs sidan 2a gäller: $\sigma_x = \nu \cdot \sigma_y$, längs sidan 2b gäller: $\sigma_y = \nu \cdot \sigma_x$.

$$m(p) = \rho \cdot V = \rho \cdot 2a \cdot 2b \cdot f/3 = \Delta p \cdot \rho \cdot 2a \cdot 2b \cdot \Delta p \cdot 2.24 \cdot 10^{-8}/3 = \Delta p \cdot 1.66 \cdot 10^{-6}$$ TDJ model

$$m(p) = \rho \cdot V = \Delta p \cdot 2.48 \cdot 10^{-7}$$ TDJ24 model



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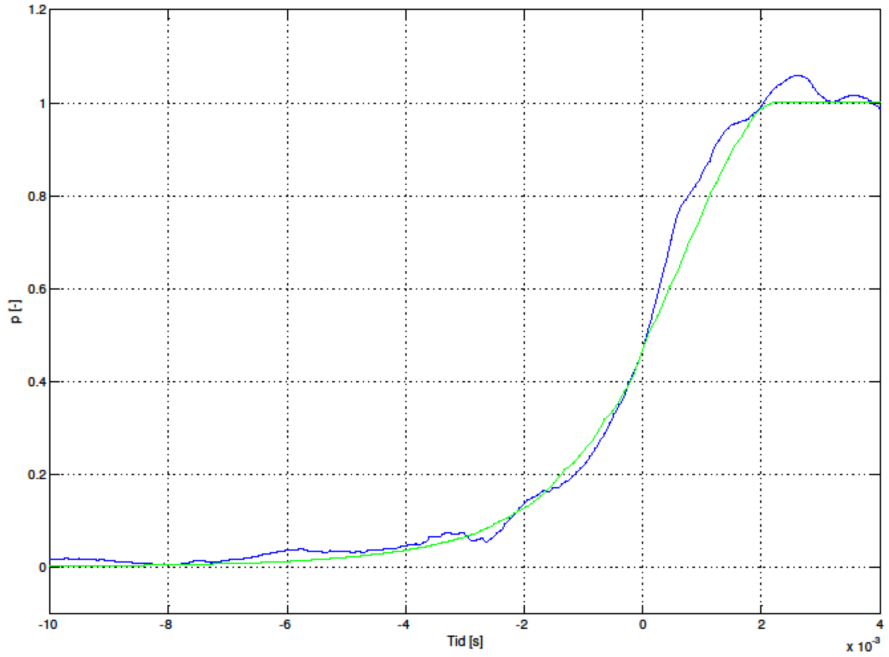
# RELAP5 vs Experiment

All the pressures have been normalized with the Joukowsky pressure



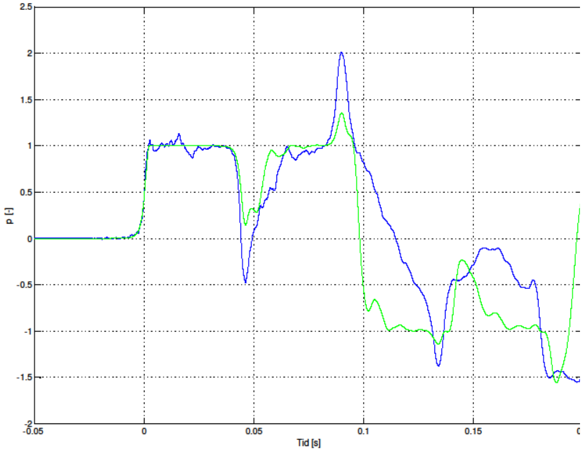

P2 pressure wave generation

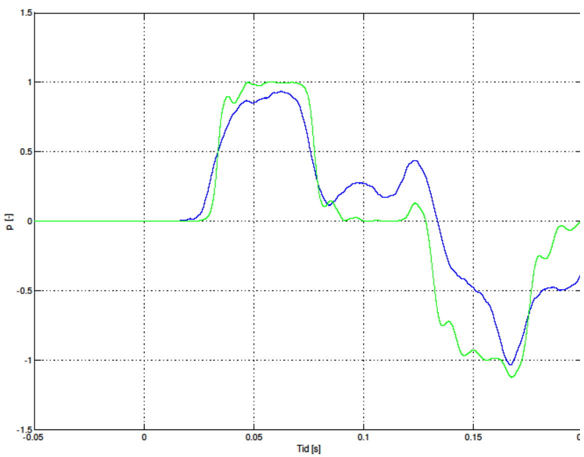
Blue: experiment, Green: RELAP5

The proper modelling of the valve closing time versus the valve area is of great importance in order to get the right shape of the gradient that generates the pressure wave. The modelling used for the simulations gives a pressure gradient quite similar to the experimental one.

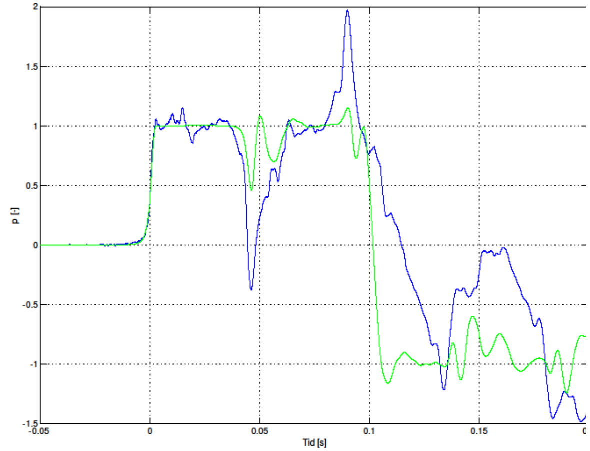
# Simple model: P2, P4

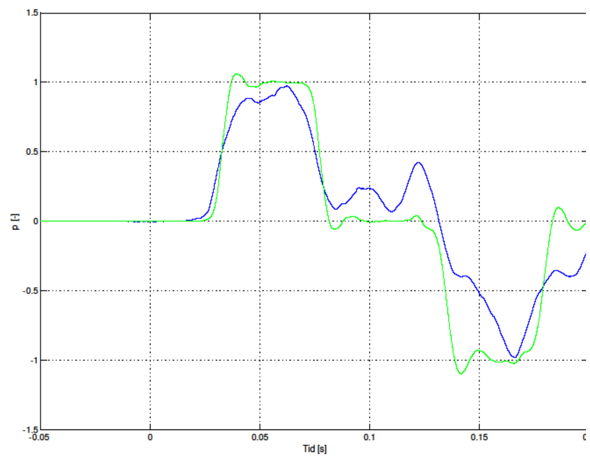
36 tubes



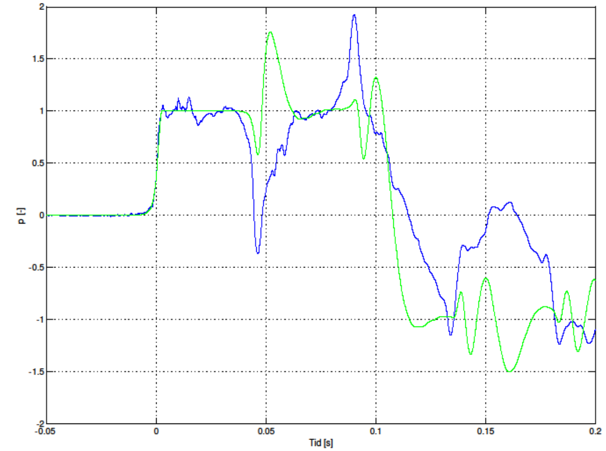



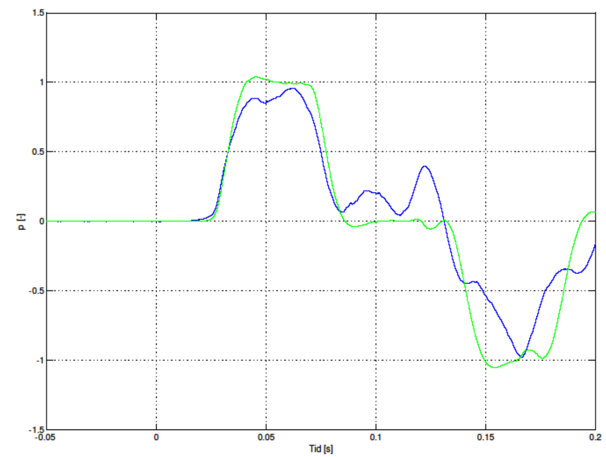

13 tubes



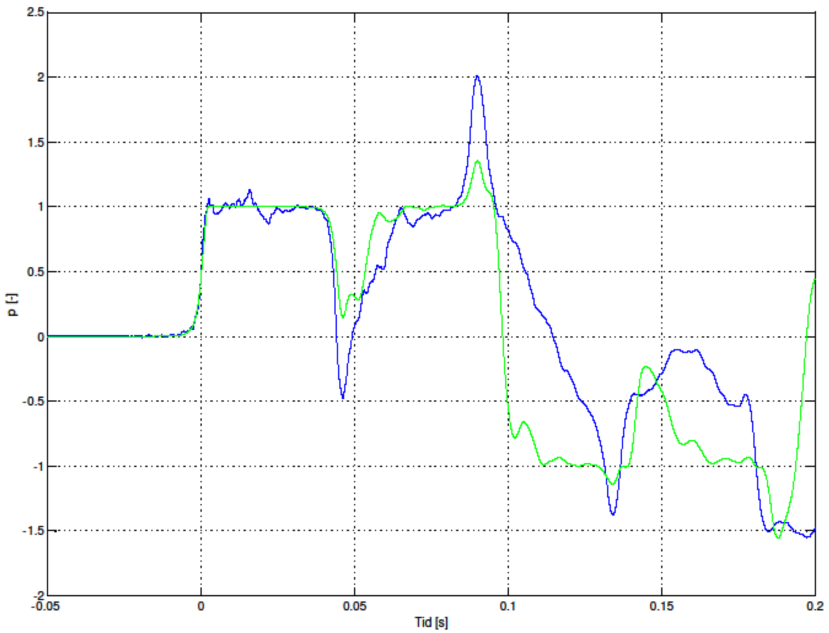

5 tubes

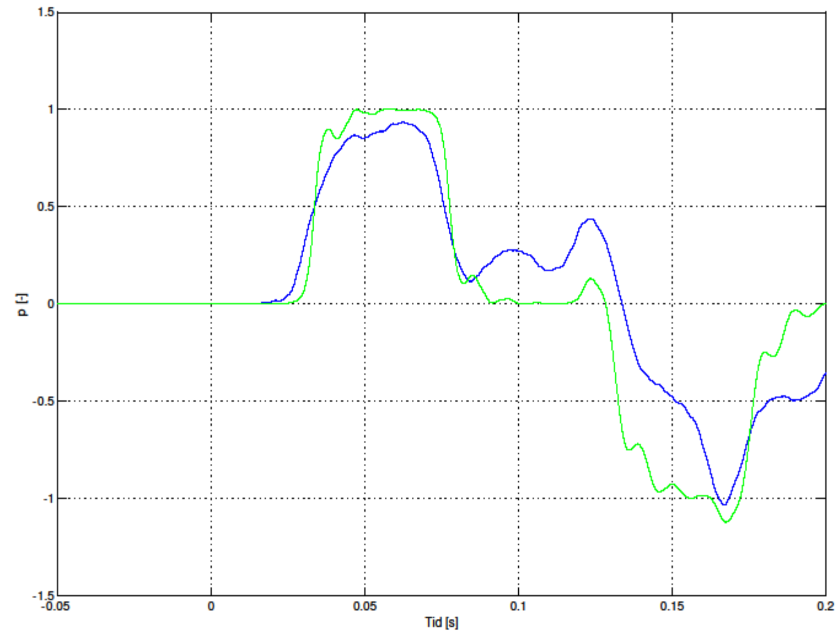


# Detailed model: P2, P4

36 tubes




The Detailed model does not give any different results compared with the simple model. The simulations take much longer time and more storing space. This model has been tested with all the mass flows all giving extremely small differences compared to the simple model.



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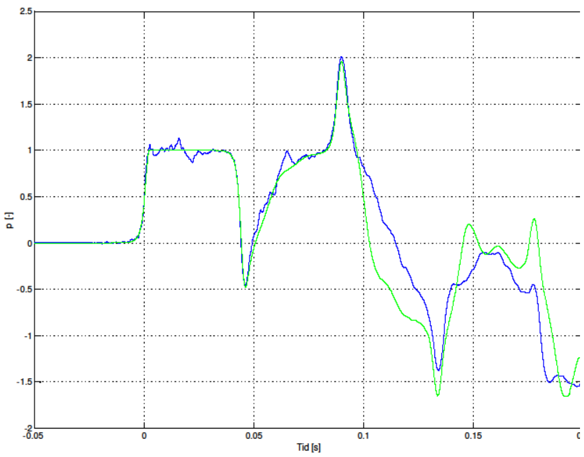
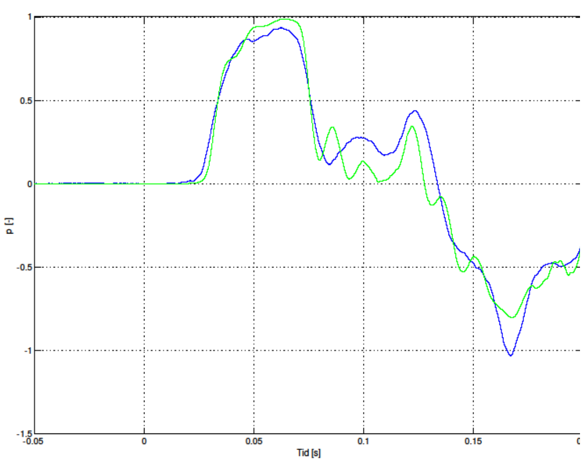
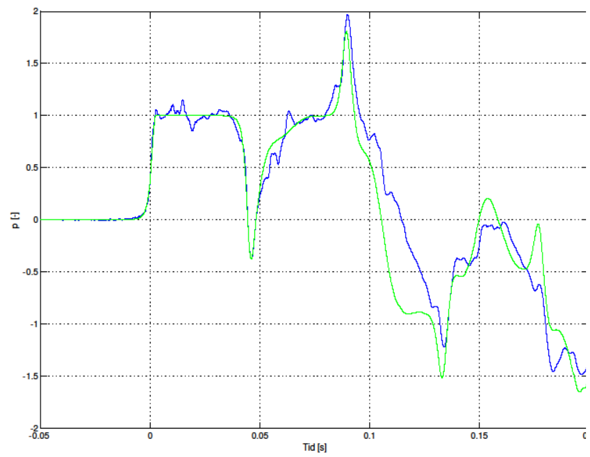
# Bubble Best fit model: P2, P4

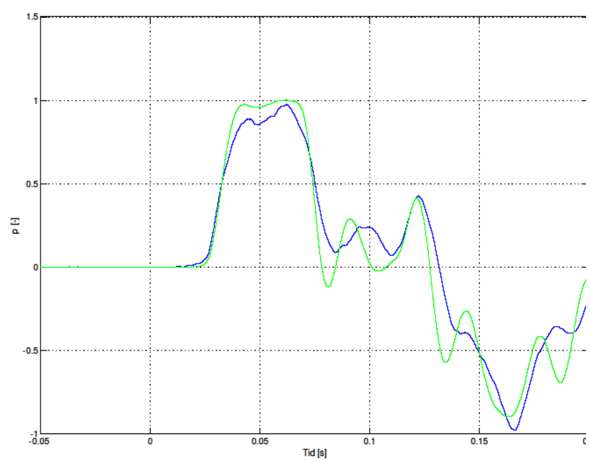
36 tubes



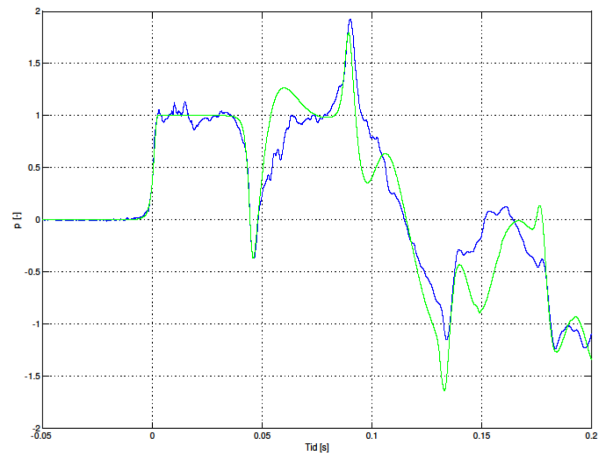



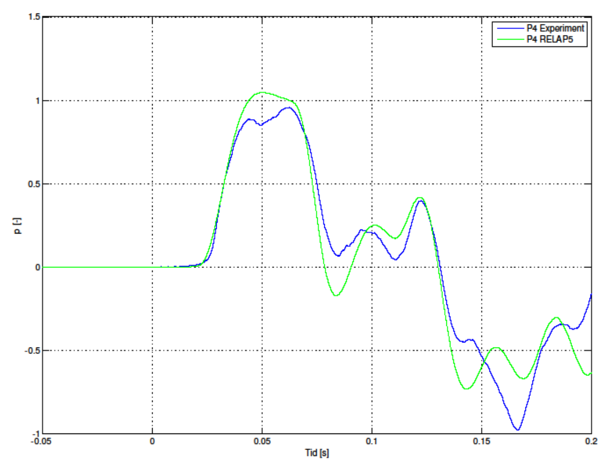

13 tubes




5 tubes



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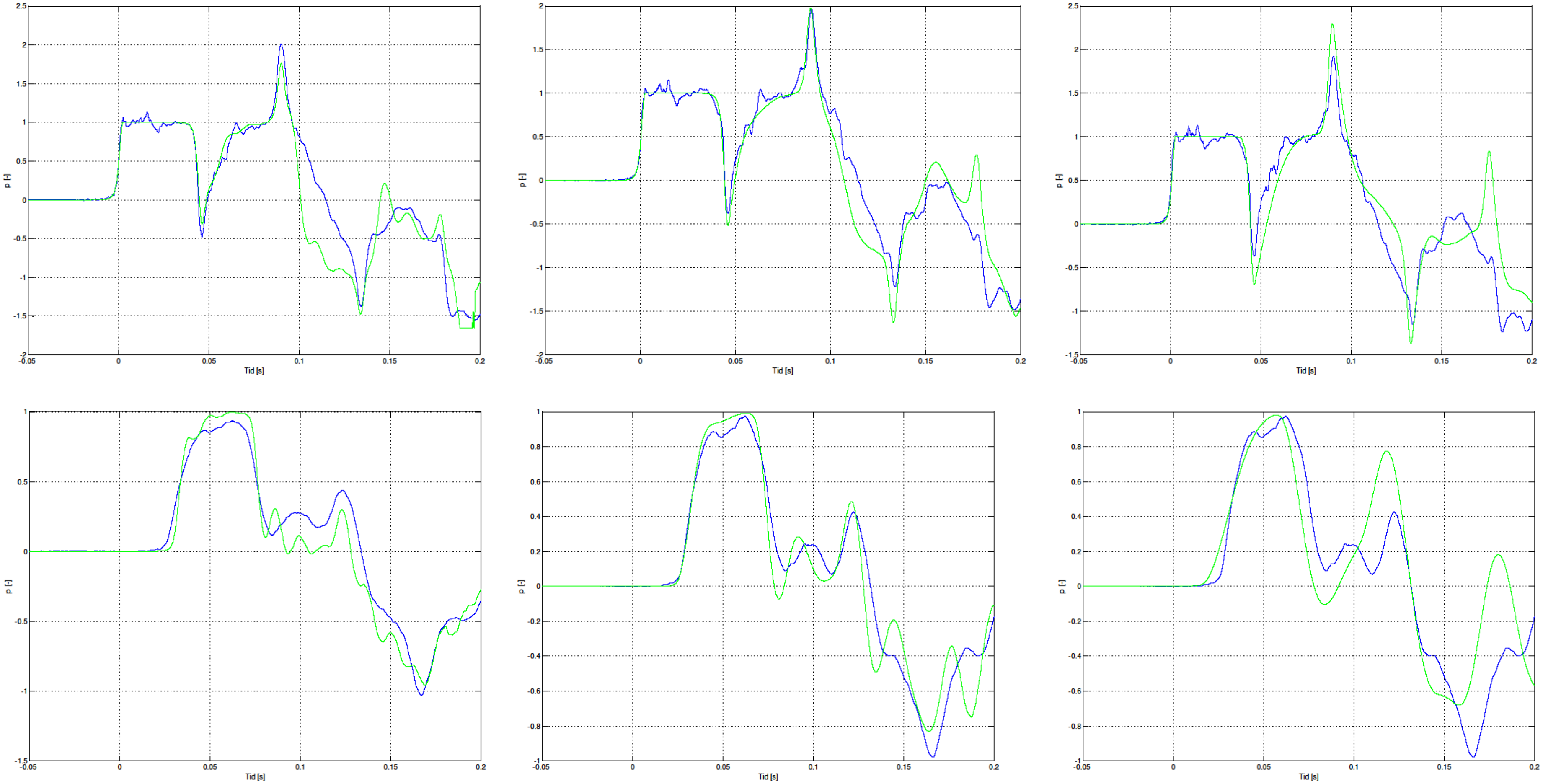
# Bubble DP24 model: P2, P4

36 tubes | 13 tubes | 5 tubes



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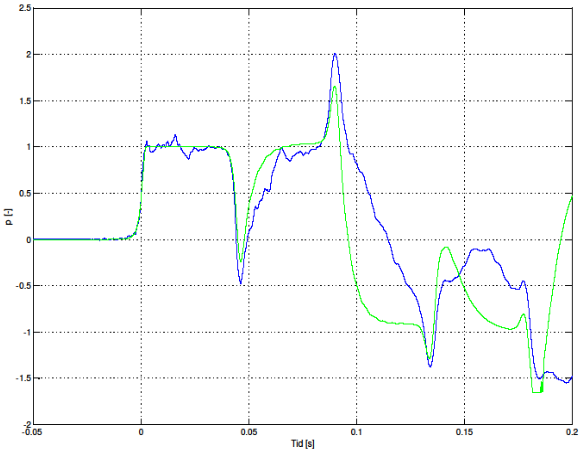
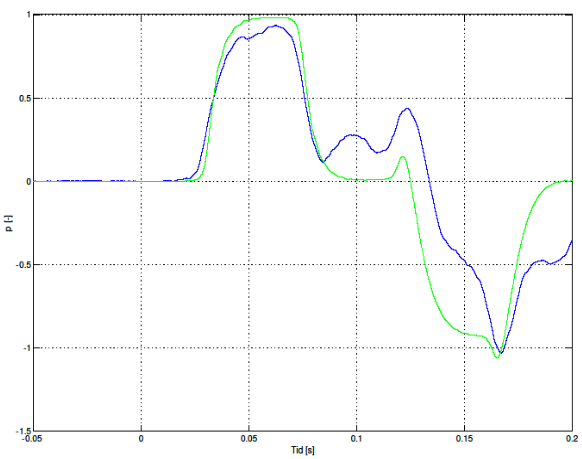
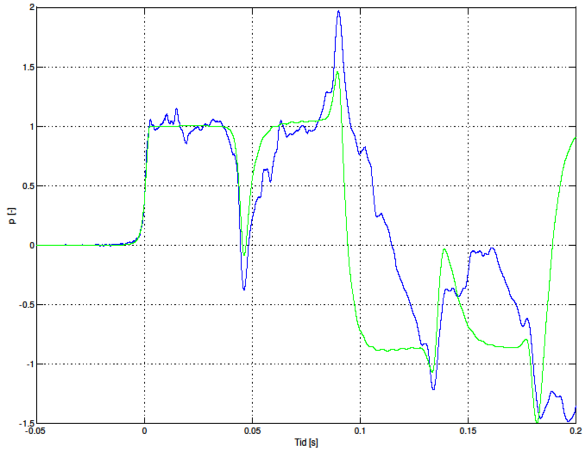
# Bubble TDJ model: P2, P4

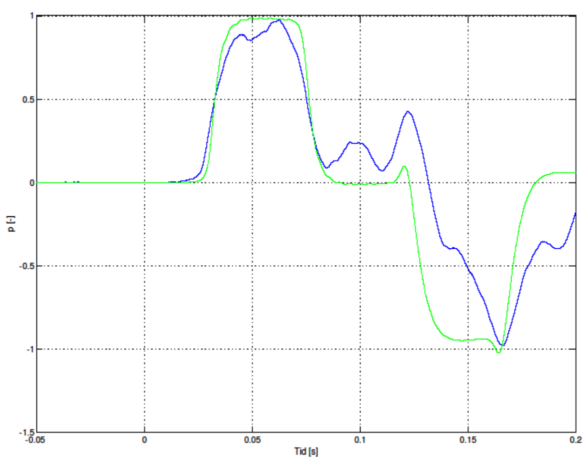
## 36 tubes



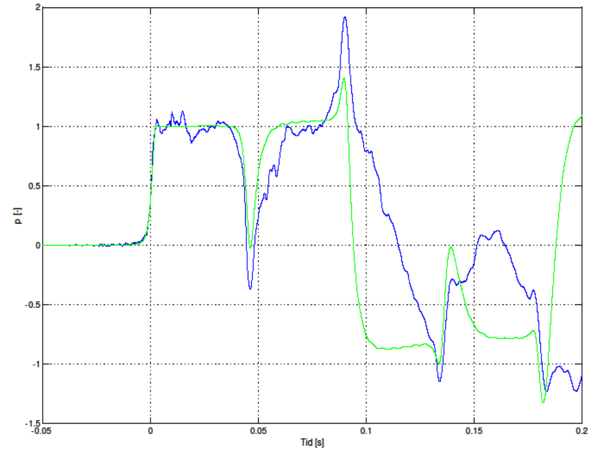



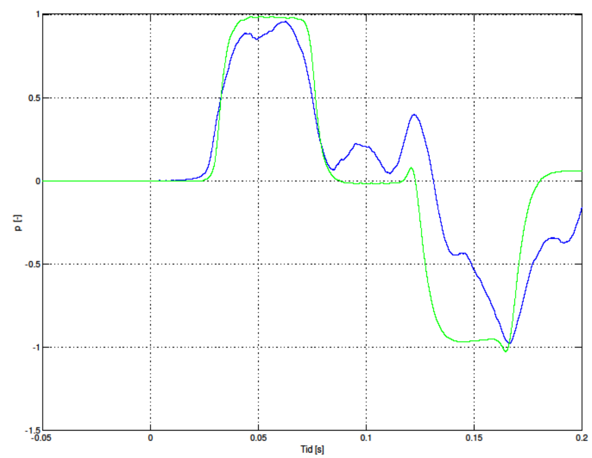

## 13 tubes



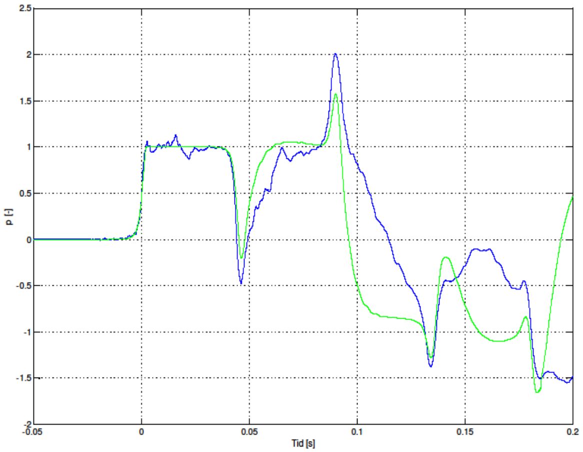

## 5 tubes

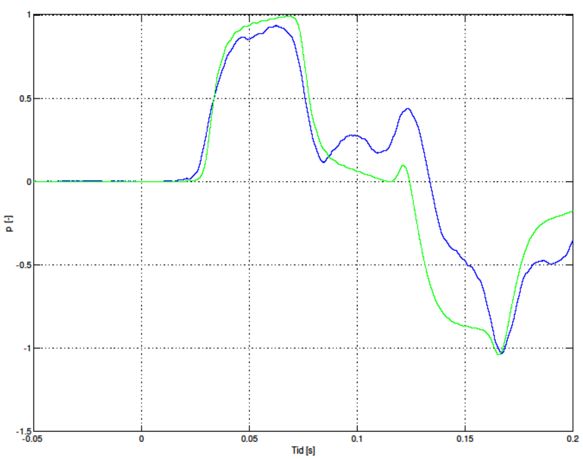


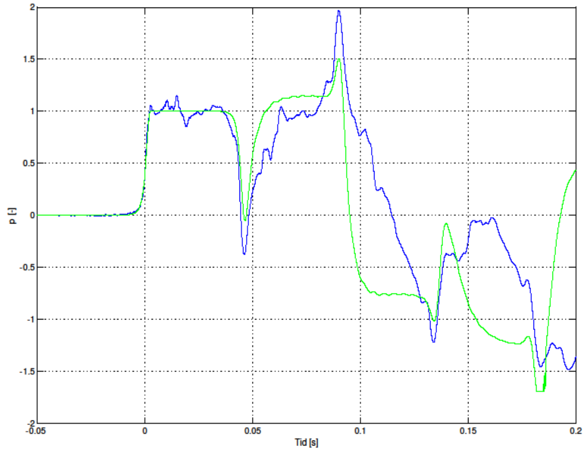
# Bubble TDJ24 model: P2, P4

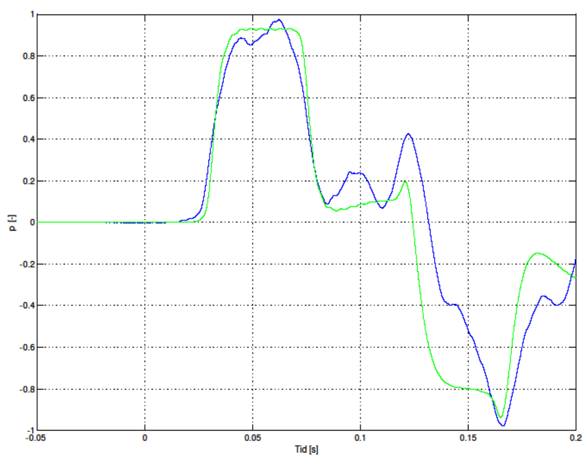
## 36 tubes



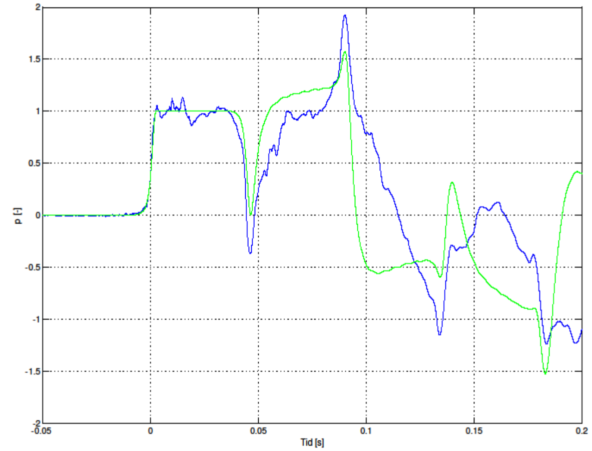



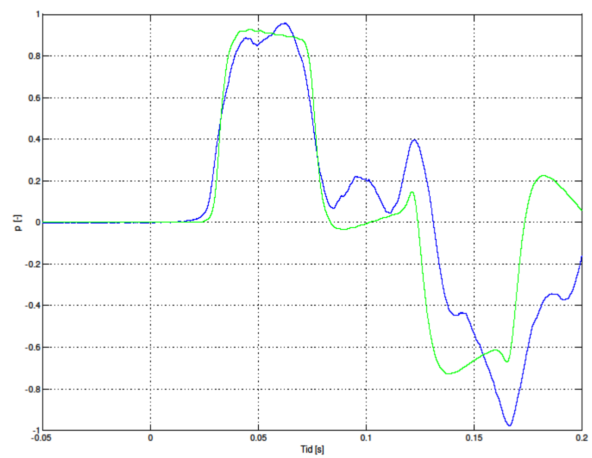

## 13 tubes



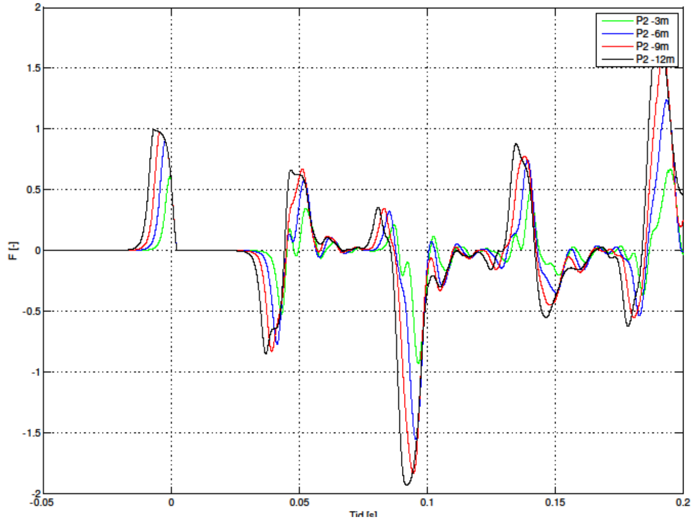

## 5 tubes

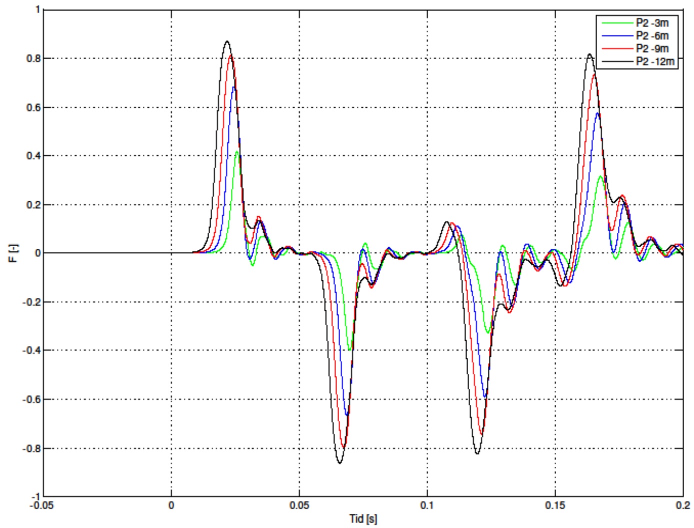


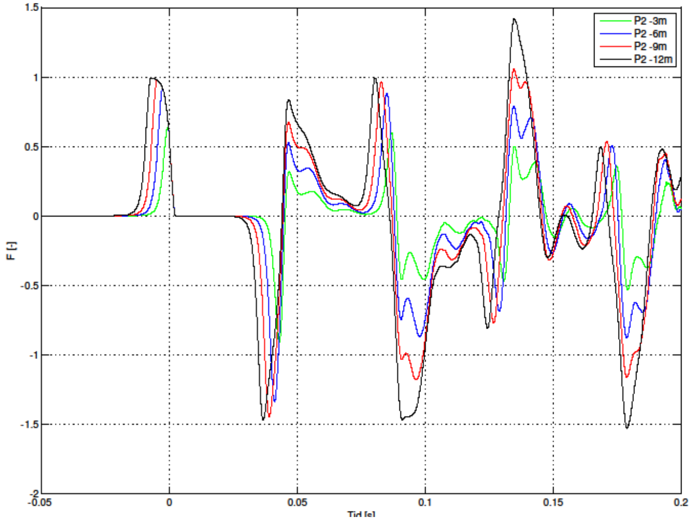
# RELAP5 Forces P2, P4

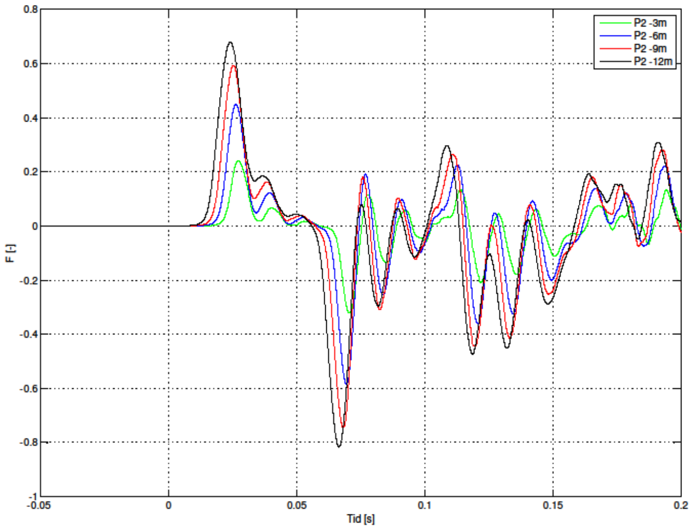
## Simple model



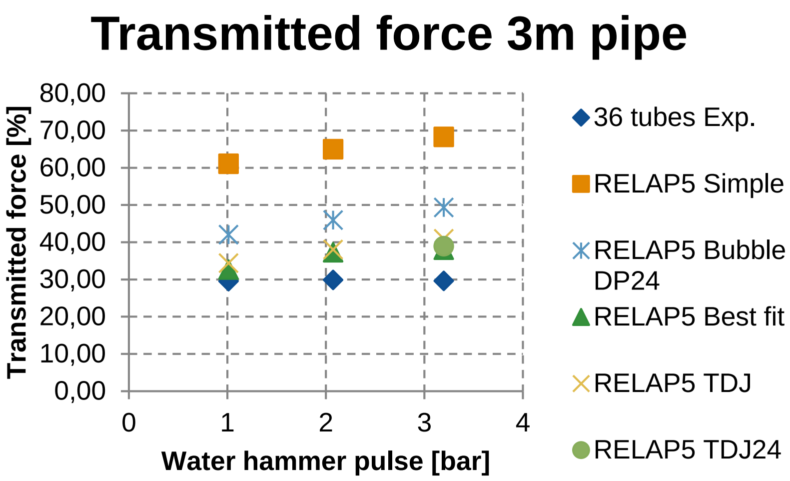



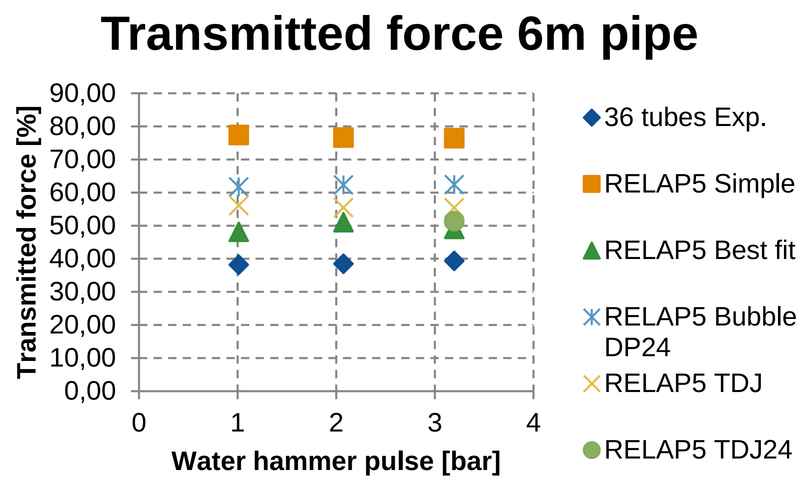

## Best fit model

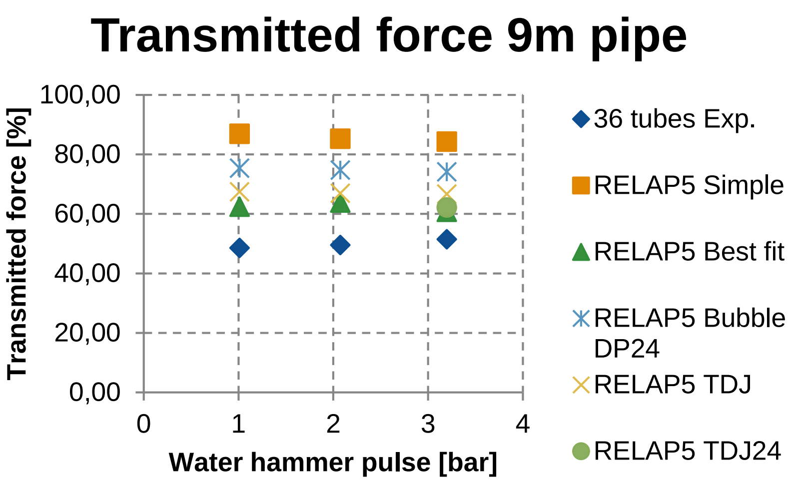


# Evaluation of forces: 36 tubes




$$\mathrm{Max}(P4-P4_{shift})/\mathrm{Max}(P2-P2_{shift})$$

# Conclusions

- The study performed for the so called “elementary components”, without fluid-structural interaction, VRD-R33:2015, showed good agreement between RELAP5 results and the calculations done using the method of characteristics MOC (and also some experimental data).
- Generally, all the developed and tested models of the heat exchanger show a rather poor agreement with the experimental data.
- Despite the fact the Simple model is built using only elementary components, it clearly denounces the limitations of RELAP5 in performing simulations where the fluid-structure interaction has a relevant role.
- The experimental data shows exactly the same behaviour of the pressure for all the configurations that have been tested. RELAP5 simple model has clearly a different response of the pressure wave for the three configurations. This further demonstrates the relevant importance of the fluid-structure interaction in the experiment that dominates on the other effects.

# Conclusions

- The theory supposes that when the pressure wave reaches the header of the tube heat exchanger it causes an expansion of the header's volume deforming the divisor plate (positioned between the headers). RELAP5 does not allow any variation of volumes in time.
- The Bubble solution allows the water to change the bubble nitrogen volume during the transient, simulating a volume expansion caused by the increasing pressure. The nitrogen is trapped in the bubble since it is located in a high point. This means it is possible to simulate an expansion and a contraction of the water volume in the header.
- The Time Dependent Junction model transfers the mass flow from one header to the other, simulating a change of volume. This means that it is possible to simulate the effects of an expansion and a contraction of the header without actually changing the volume. Anyway, this method transfers also the pressure information between the two headers.

# Further considerations

- The static structural analysis is based on a constant pressure difference over the divisor plate between the headers. In this way it has been possible to estimate the volume generated by the bended plate. This is of course a great simplification of the dynamics of the divisor plate during the transient. It is hard to imagine that the plate will be able to reach a deformation equal to the static case. The dynamic response will be ruled by inertia of the plate and the changing pressure difference on the two sides.
- A fundamental experiment to be performed consists in changing the thickness of the divisor plate in order to prove that the static structural analysis can actually be a good approximation for building a RELAP5 model based on bubble size and also in order to see how this parameter affects the fluid-structure interaction.

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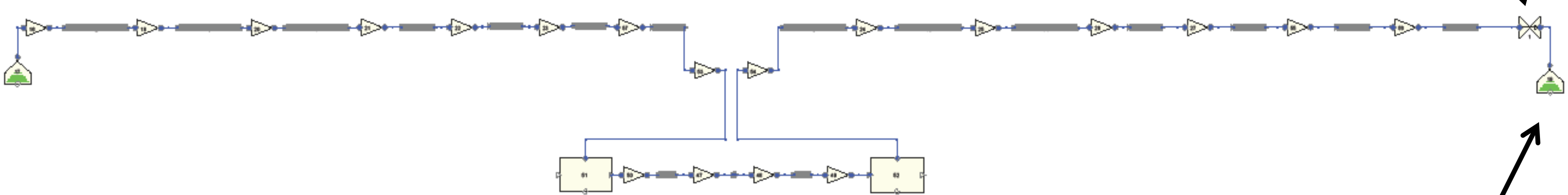
# Extra material

# RELAP5 modelling of test rig

Time Dependent Volume with a constant temperature (293.15 K) and pressure calibrated to have the desired mass flow rate

30 meters long pipe with inner diameter 0.1 m, nodalization L/D=1

valve



heat exchanger section

Time Dependent Junction with a constant temperature (293.15 K) and pressure (10e6 Pa)



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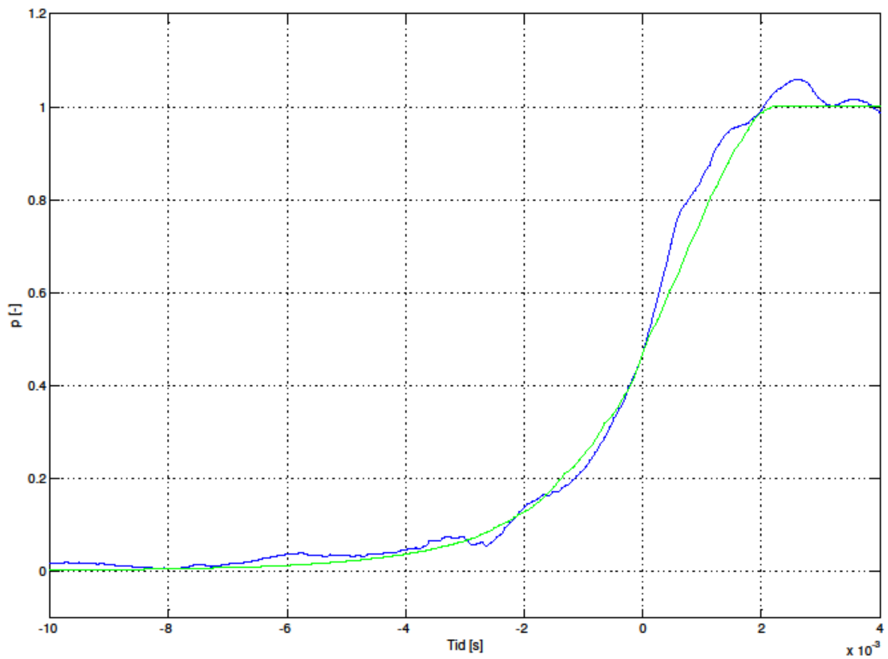
# RELAP5 modelling of the closing valve

All the pressures have been normalized with the Joukowsky pressure




P2 pressure wave generation

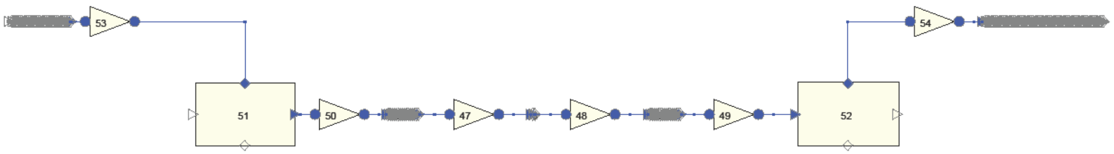
Blue: experiment

Green: RELAP5

The proper modelling of the valve closing time versus the valve area is of great importance in order to get the right shape of the gradient that generates the pressure wave.

The modelling used for the simulations gives a pressure gradient quite similar to the experimental one.

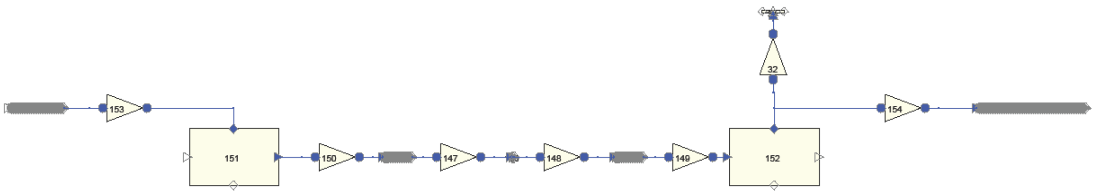
# RELAP5 tube heat exchanger: Simple model




The Headers are modelled with a single horizontal volume. The chosen geometrical parameters are the total volume, the area and the hydraulic diameter in the X direction, the length in the Y direction

The tubes are modelled with three in-line pipe components using the same equivalent length, total area and equivalent diameter as the tubes in the experimental setup

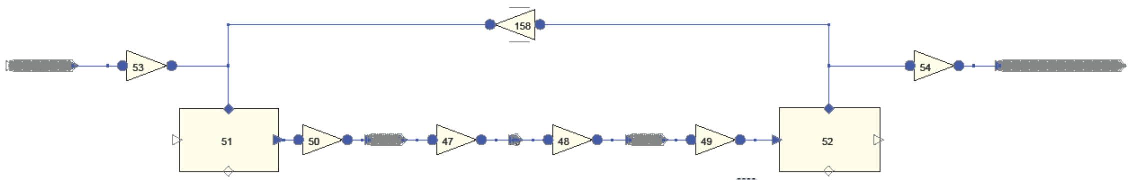
# RELAP5 tube heat exchanger: Bubble model

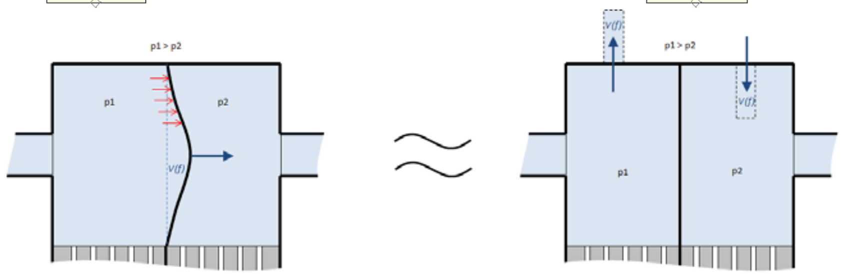


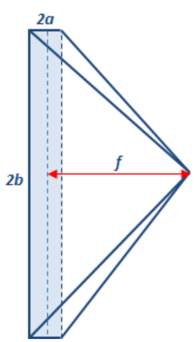

A single vertical volume, containing Nitrogen at 293.15 K and 10e6 Pa, is added and coupled to the exit Header of the heat exchanger through a Single Junction.

The bubble volume is used in order to simulate the effects of the compressibility-deformation of the metal structure. The pressure wave creates a variation of the volume in the Headers, mainly because of the deformation of the plate divisor (positioned between the headers).

# RELAP5 tube heat exchanger: Time Dependent Junction



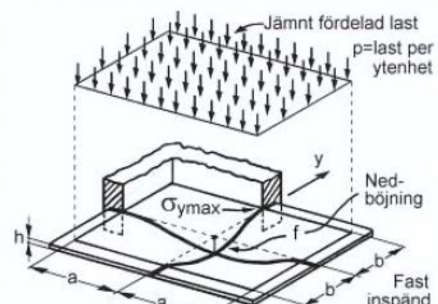




$$V = 2a \cdot 2b \cdot f / 3$$

$$f = 0.35 \cdot \frac{\Delta p \cdot b^4}{E \cdot h^3} = \Delta p \cdot 2.24 \cdot 10^{-8}$$

**Spänningar och formändringar i fast inspänd rektangulär platta påverkad av en jämnt fördelad last**




Jämnt fördelad last p·2a·2b över rektangulär platta, fast inspänd längs alla fyra sidorna. Den största spänningen uppträder vid inspänningen mitt på den längre sidan 2a. Den går i y-riktning och betecknas $\sigma_{ymax}$

| Sidoförhållande | Nedböjning | Spänningar i plattans mitt | | |
|---|---|---|---|---|
| $\frac{2a}{2b}$ | $\frac{f}{\frac{pb^4}{Eh^3}}$ | $\frac{\sigma_x}{\frac{pb^2}{h^2}}$ | $\frac{\sigma_y}{\frac{pb^2}{h^2}}$ | $\frac{\sigma_{ymax}}{\frac{pb^2}{h^2}}$ |
| 1,0 | 0,225 | ±0,53 | ±0,53 | ±1,24 |
| 1,5 | 0,394 | ±0,48 | ±0,88 | ±1,82 |
| 2,0 | 0,431 | ±0,31 | ±0,94 | ±1,92 |
| ∞ | 0,455 | ±0,30 | ±1,00 | ±2,00 |

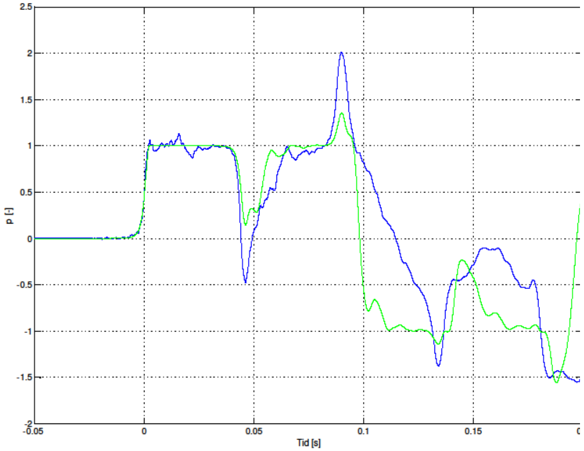
Krökningen vid inspänningen är den motsatta mot krökningen i mitten. Spänningarna vid inspänningen har då motsatta tecken jämfört med spänningarna i mitten. Vid inspänningen längs sidan 2a gäller: $\sigma_x = \nu \cdot \sigma_y$, längs sidan 2b gäller: $\sigma_y = \nu \cdot \sigma_x$.

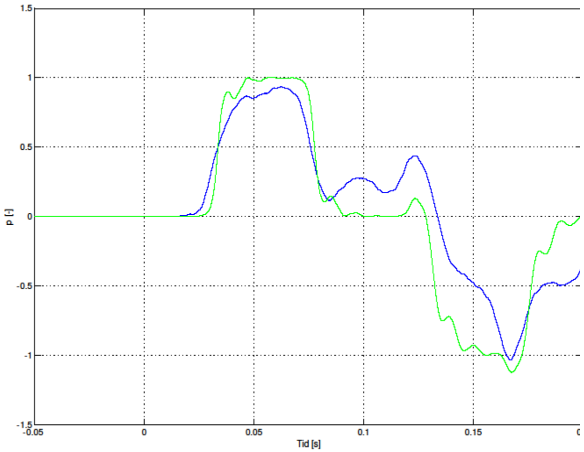
$$m(p) = \rho \cdot V = \rho \cdot 2a \cdot 2b \cdot f / 3 = \Delta p \cdot \rho \cdot 2a \cdot 2b \cdot \Delta p \cdot 2.24 \cdot 10^{-8} / 3 = \Delta p \cdot 1.66 \cdot 10^{-6}$$ TDJ model

$$m(p) = \rho \cdot V = \Delta p \cdot 2.48 \cdot 10^{-7}$$ TDJ24 model

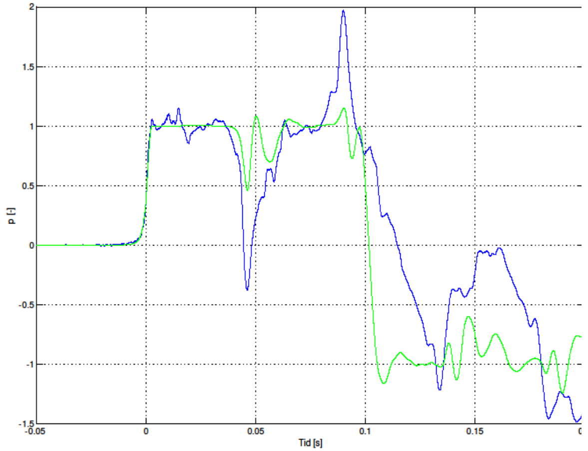
# Simple model: P2, P4

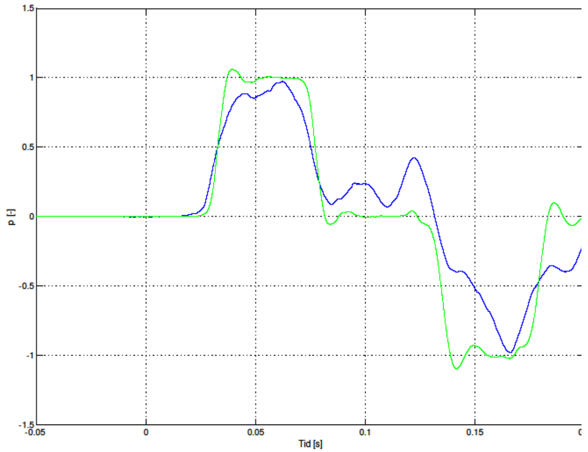
## 36 tubes



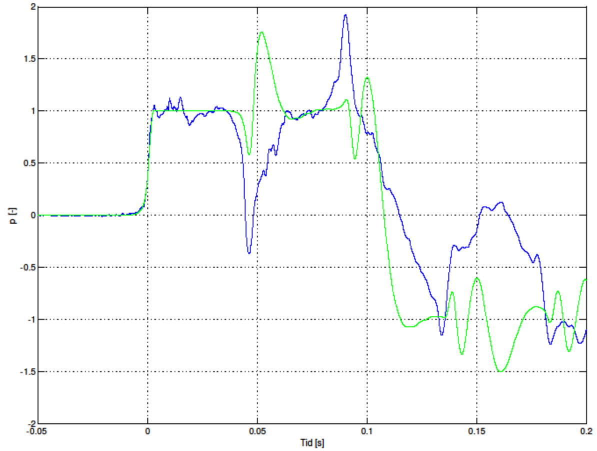



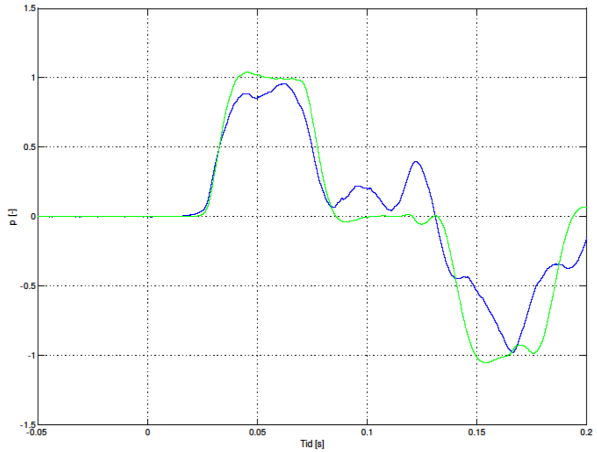

## 13 tubes




## 5 tubes



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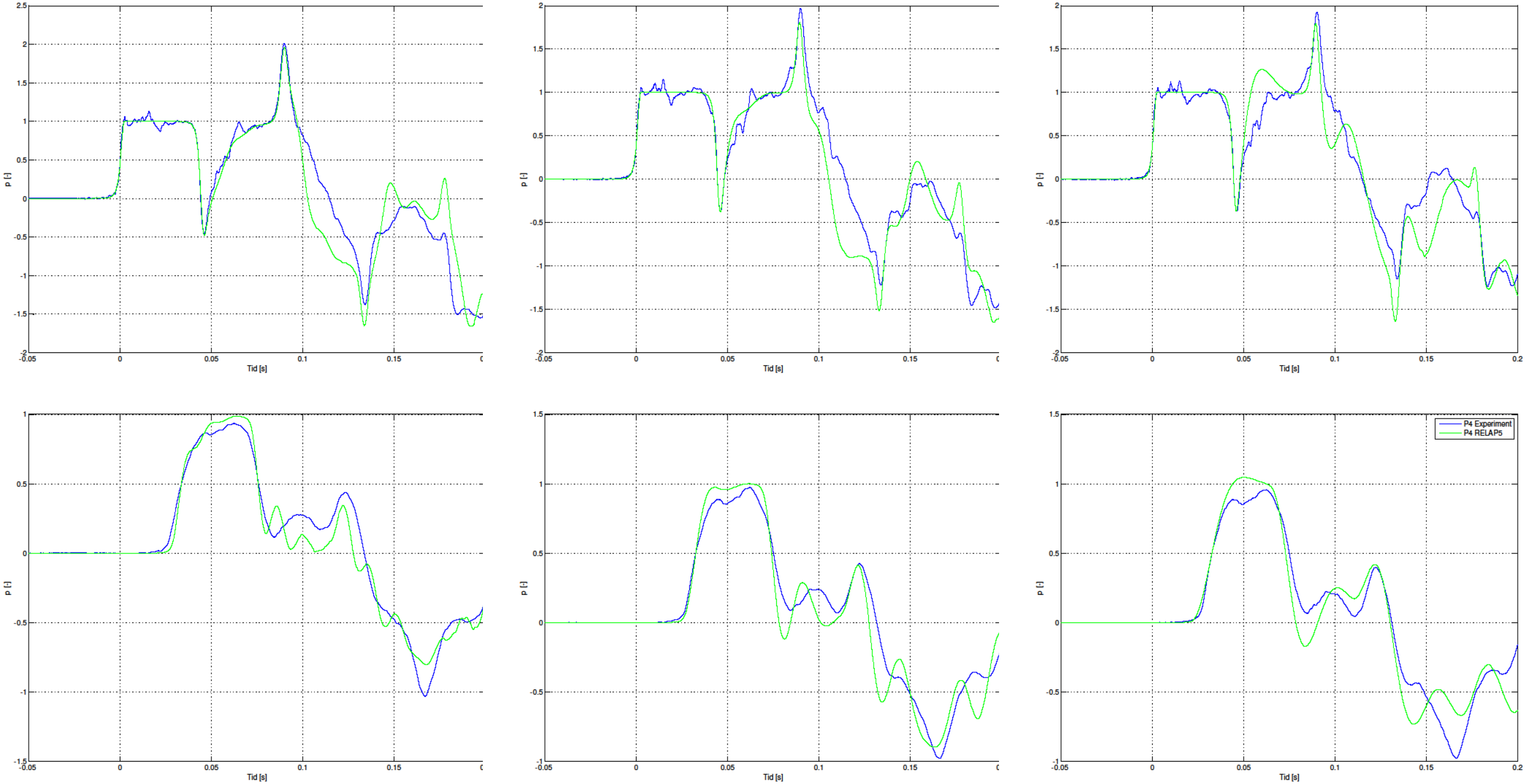
# Bubble model: P2, P4

36 tubes | 13 tubes | 5 tubes



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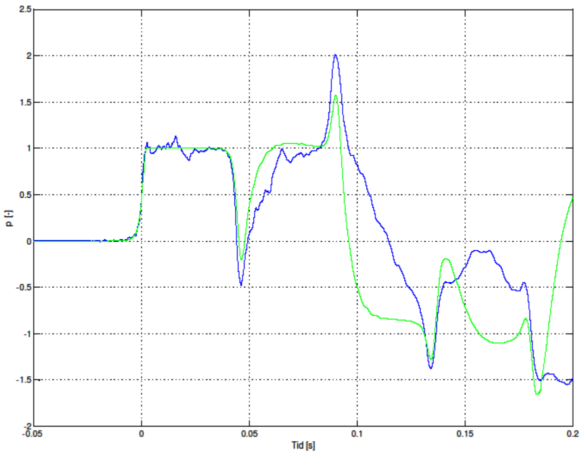
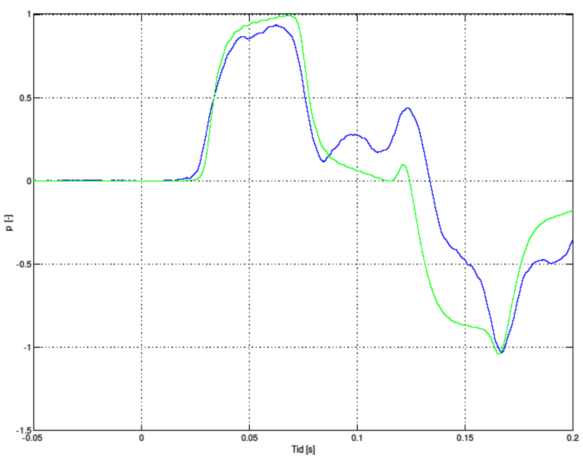
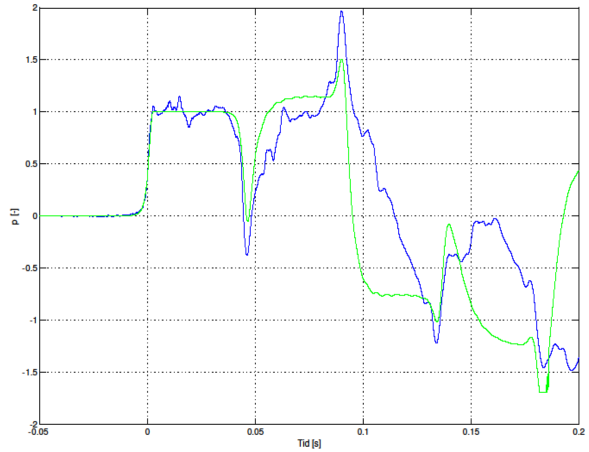
# TDJ model: P2, P4

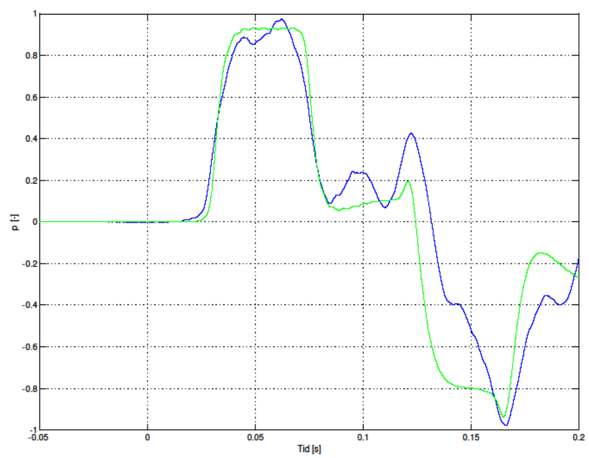
## 36 tubes



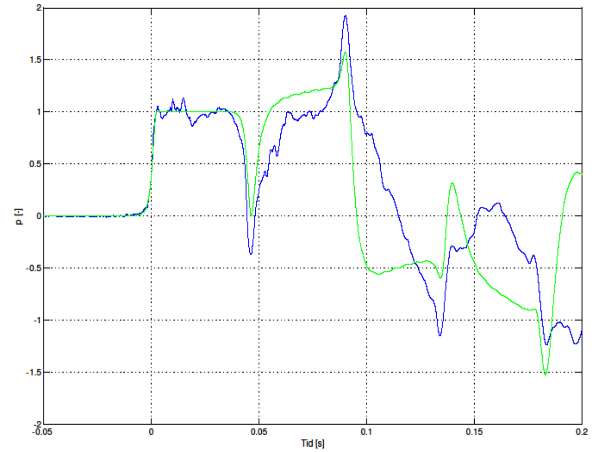



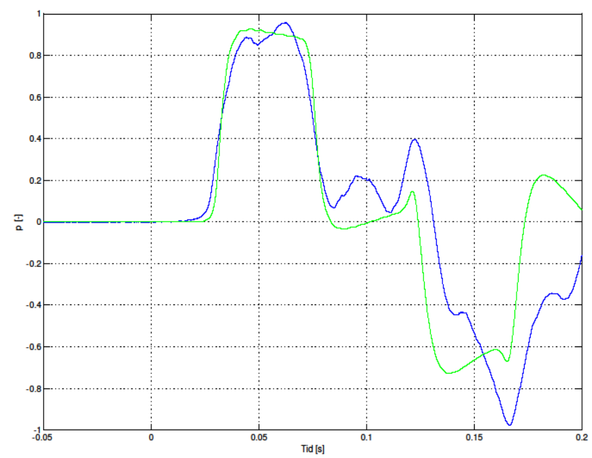

## 13 tubes




## 5 tubes



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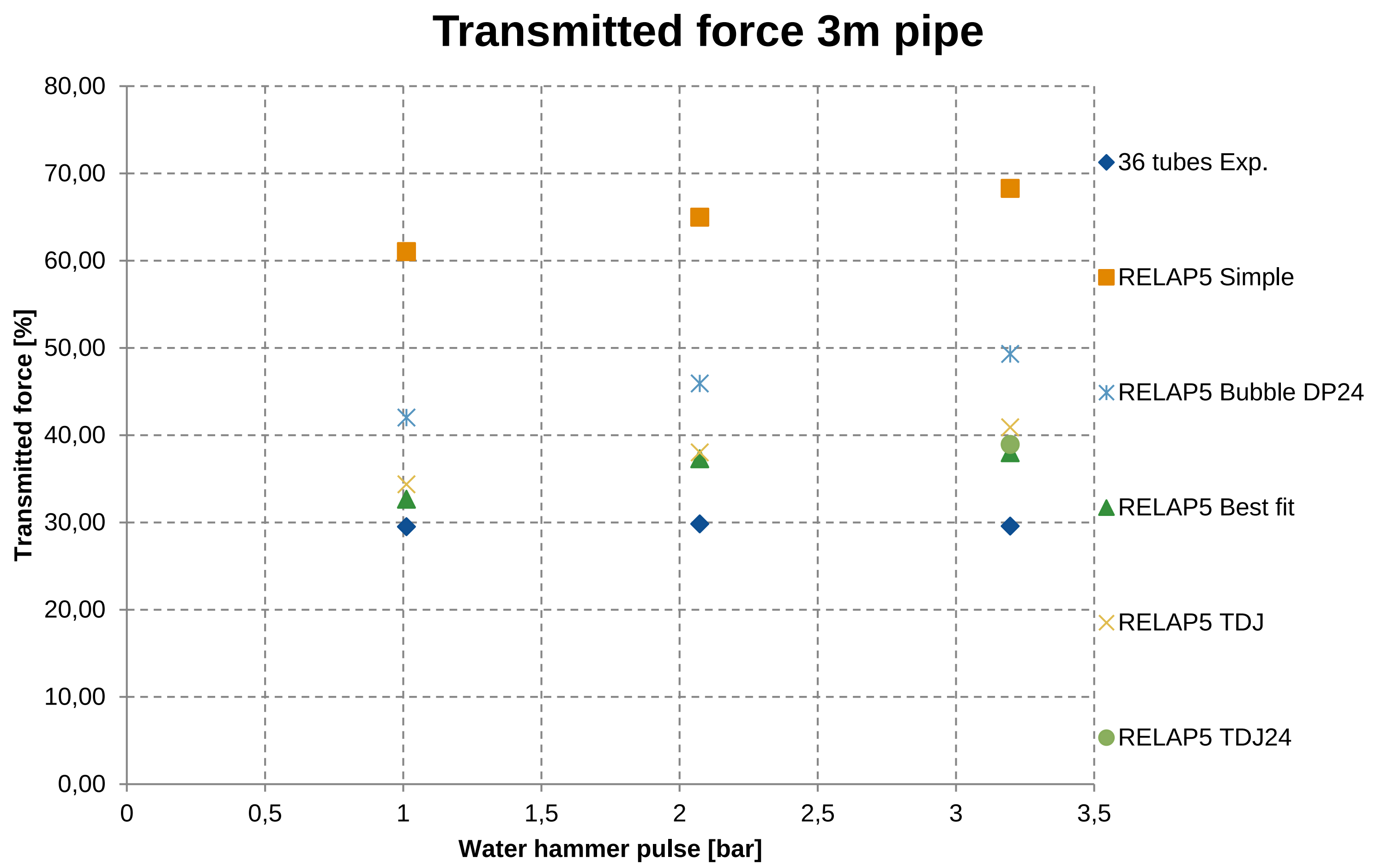
# Evaluation of forces: 36 tubes



# Conclusions

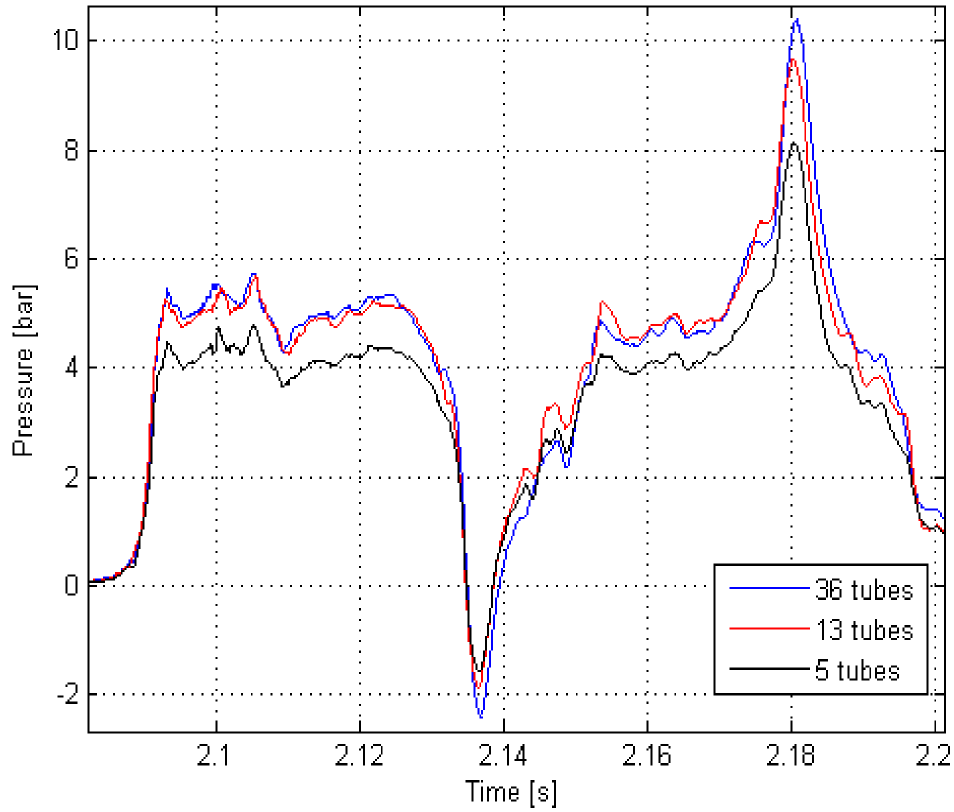
- The Simple model is built using only elementary components, and shows the limitations of RELAP5 in performing simulations where the fluid-structure interaction has a relevant role. RELAP5 does not allow any variation of volumes in time.

- The Bubble model allows one to simulate an expansion and a contraction of the water volume in the header. The water changes the nitrogen bubble volume during the transient, simulating a chamber volume expansion caused by the increasing pressure.

- The Time Dependent Junction model transfers mass from one header to the other, simulating a change of volume. This means that it is possible to simulate the effects of an expansion and a contraction of the header without actually changing the volume.

# Extra material

# Pressure wave propagation: P2



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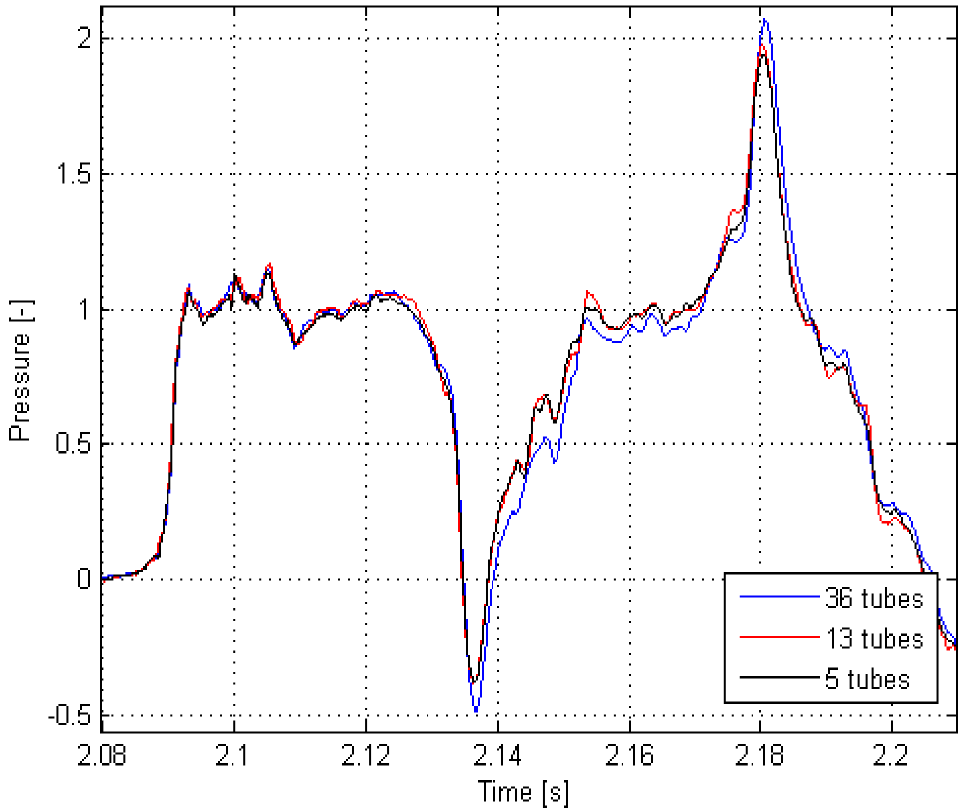
# Pressure wave propagation: P2 normalized $\Delta p = \rho\, c\, \Delta v$



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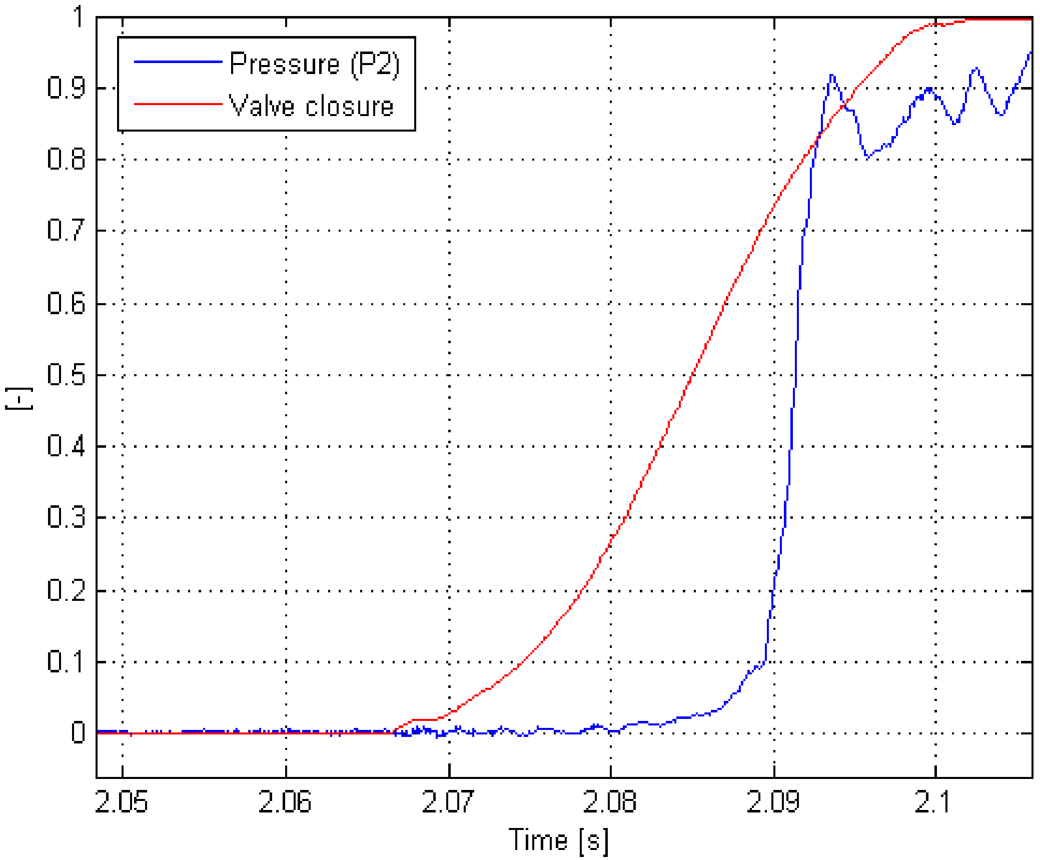
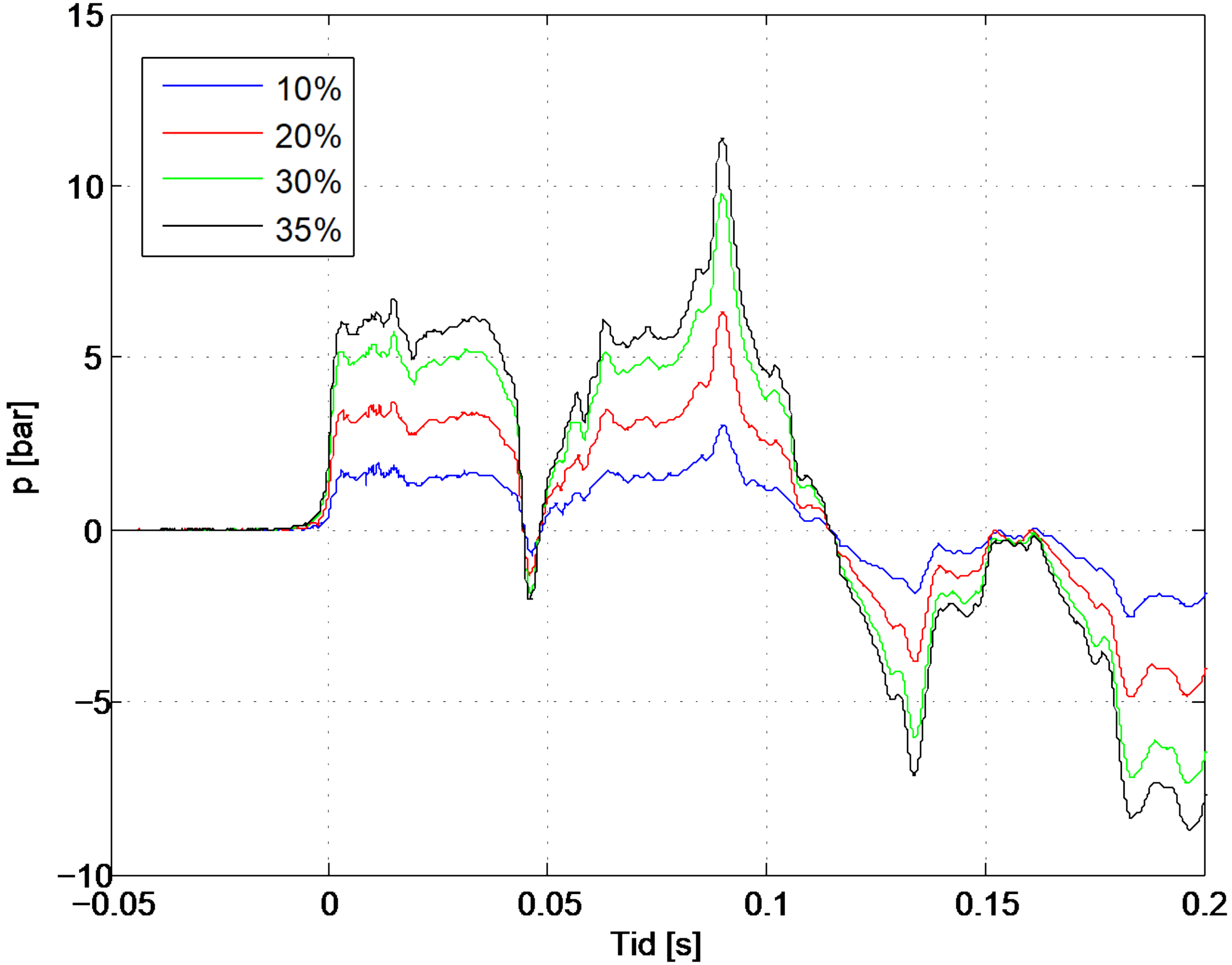
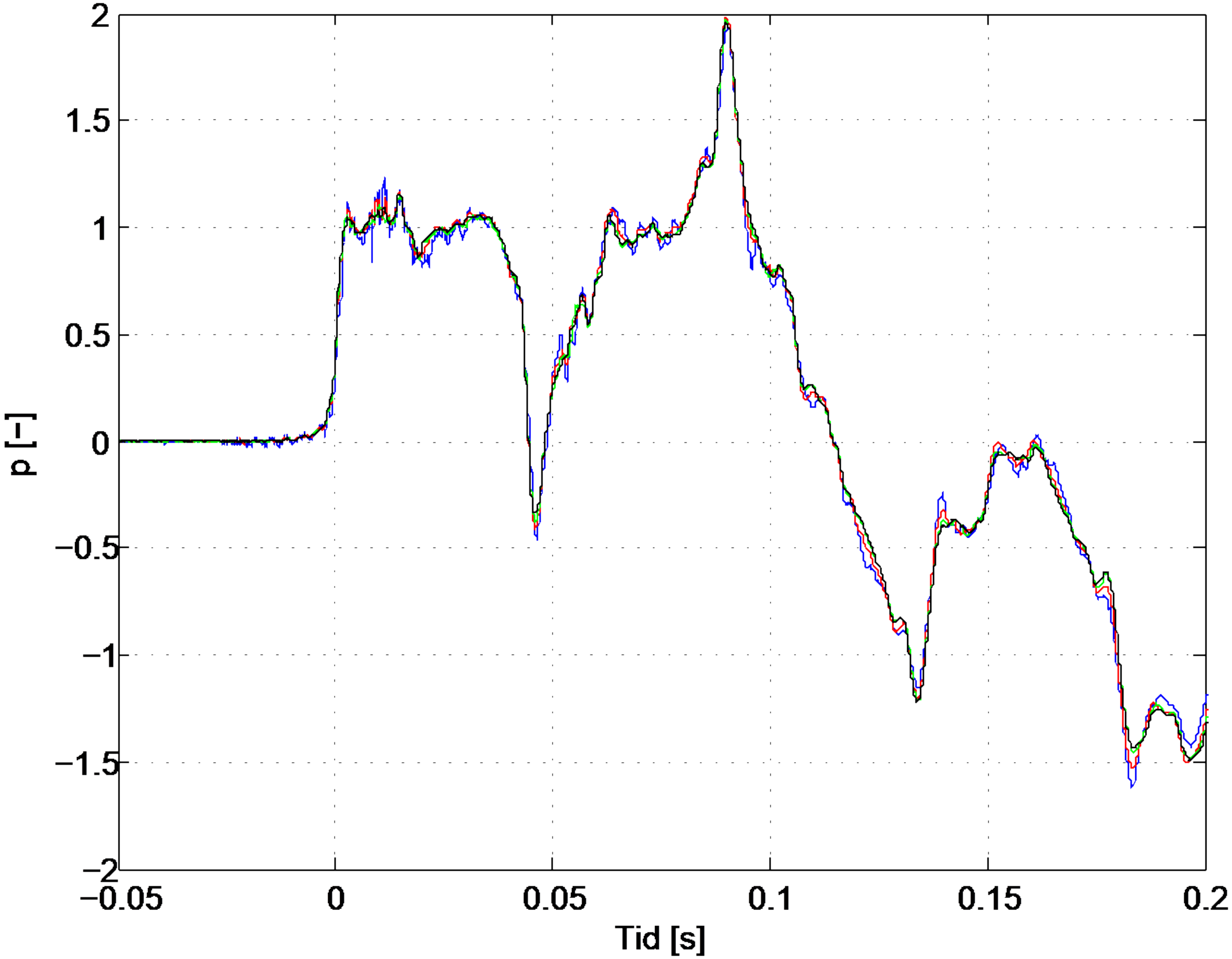
# Extra material



# Experimental results: P2, all mass flow rates



# Experimental results: P2 Normalized Joukowsky ρcΔV



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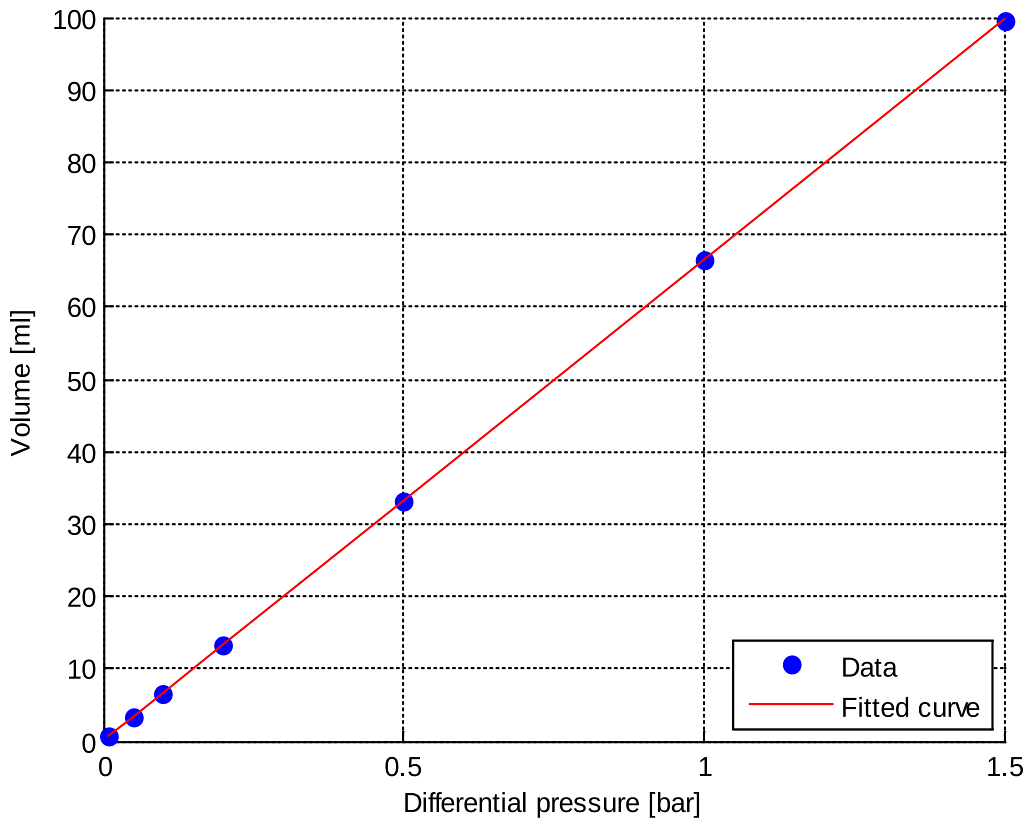
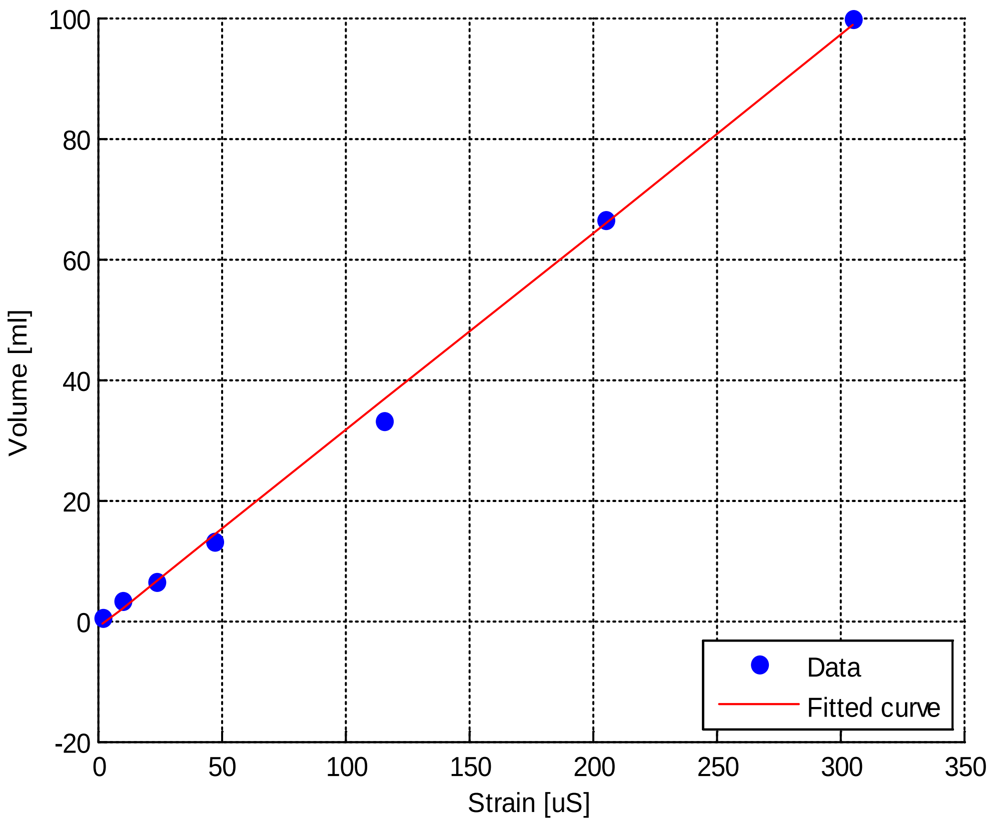
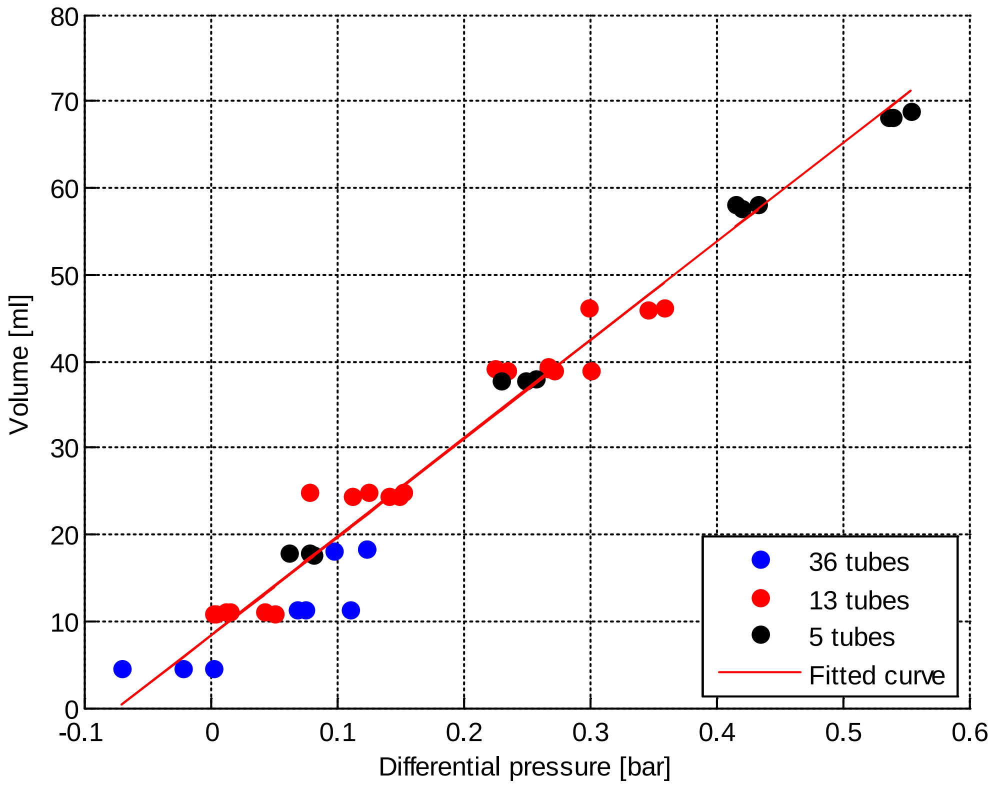


# Extra material



# FSI chamber wall



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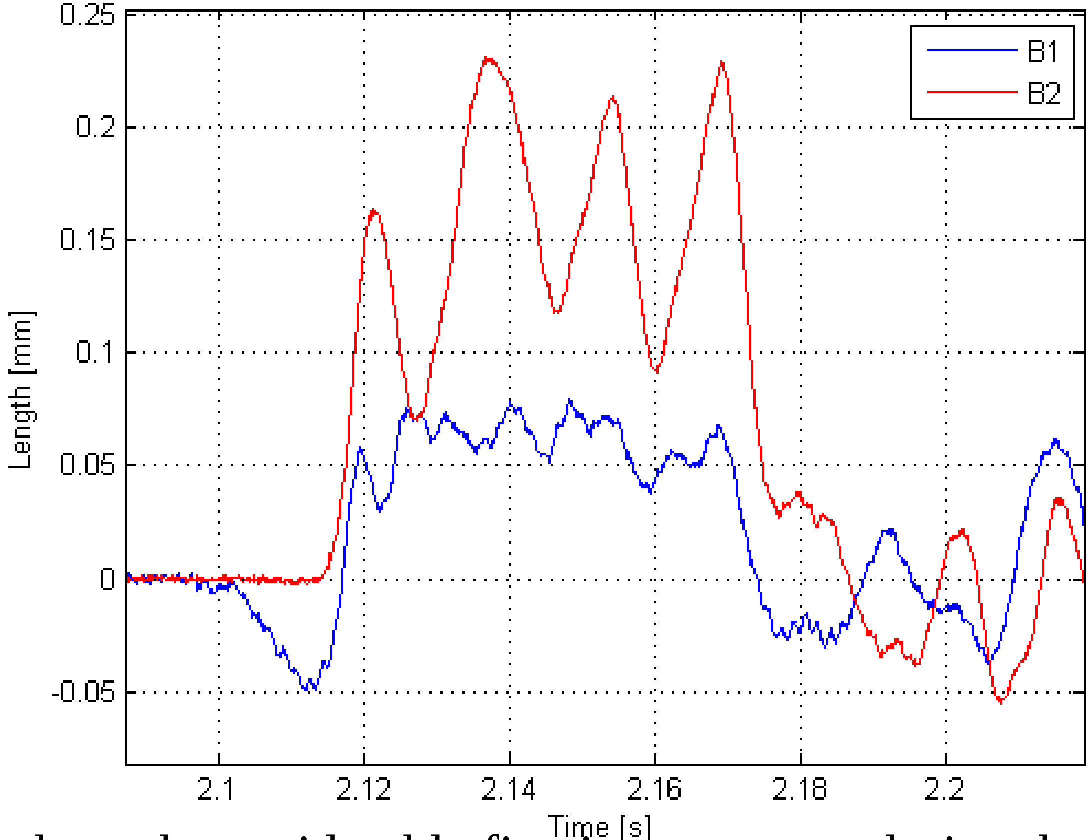


The test rig went through considerable fixating measures during the trial period to make the test rig more rigid and less susceptible to FSI problems. The movement of the test rig measured by the displacement sensors, was reduced from 10 mm to less than 0.3 mm

# Extra material

# Future considerations

- The static structural analysis is based on a constant pressure difference over the divisor plate between the headers. In this way it has been possible to estimate the volume generated by the bended plate. This is of course a great simplification of the dynamics of the divisor plate during the transient. It is hard to imagine that the plate will be able to reach a deformation equal to the static case. The dynamic response will be ruled by inertia of the plate and the changing pressure difference on the two sides.

- A fundamental experiment to be performed consists in changing the thickness of the divding plate in order to prove that the static structural analysis can actually be a good approximation for building a RELAP5 model based on bubble size and also in order to see how this parameter affects the fluid-structure interaction.