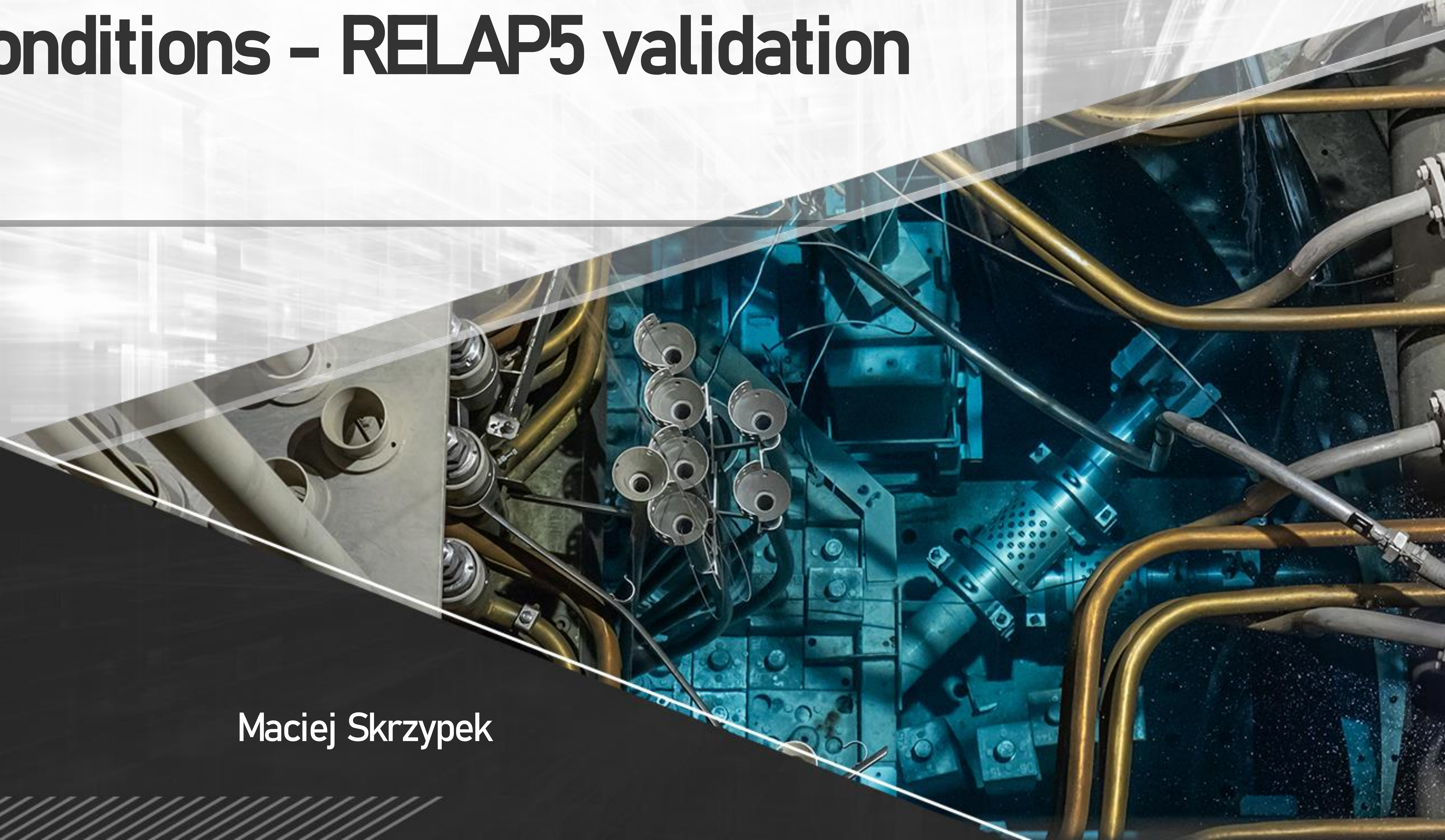
November 16, 2021

Study of natural circulation in steady states conditions - RELAP5 validation



NARODOWE
CENTRUM
BADAŃ
JĄDROWYCH
ŚWIERK

Maciej Skrzypek

Agenda

- Introduction and work motivation
- Project goal
- Facility description
- RELAP5 code, model and nodalization
- Experiment conditions
- Code version and CPU statistics
- Simulation results
  - Stable conditions (107 cases)
  - Sensitivity analysis – parameter study
- Conclusions and future plans

Introduction

- Work presented in this report is a result of collaboration of National Centre for Nuclear Research -NCBJ and University of Illinois at Urbana-Champaign- UIUC where NCBJ’s specialist has completed an internship.
- Experiments have been performed in the Multiphase Thermo-fluid Dynamics Laboratory (MTDL) at the University of Illinois at Urbana-Champaign including steady-state natural circulation conditions with and without steady periodic oscillations. After that the simulations using RELAP5 code were performed.
- All the results of simulations are collected in the report NUREG. This presentation briefly describes the main outcomes.

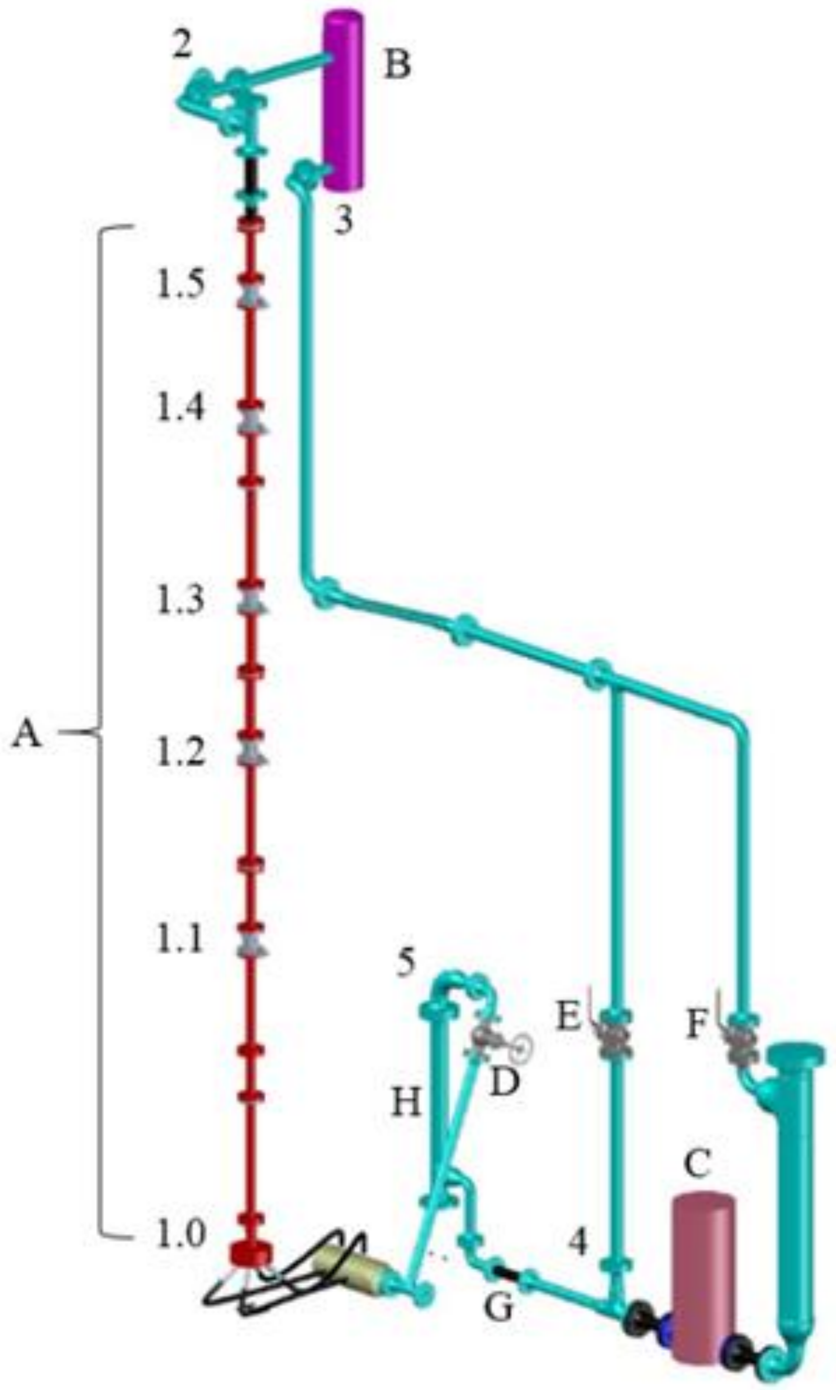
Project goal

- Analyzing the natural circulation data to validate the code by the comparison of the measured data with results of RELAP5 mod 3.3. model simulation.
- The simulation code results were compared to the experimental measurement of *void fraction, pressure, temperature* and *flow rate.*
- Under the project the focus was on the validation of RELAP5 under: stable and unstable conditions (periodic oscillation), as the two-phase natural circulation is prone to instabilities due to the coupling of the flow rate and void fraction. These conditions have a repeatable oscillation in systems parameter under steady-state boundary conditions, representing a challenging application for system analysis codes (2nd stage, described in [2])
- In this presentation only non-oscillation conditions will be shown.

Facility description

- The experimental loop facility, with 5m vertical annulus test section, can span a wide range of pressure, heat flux, liquid subcooling, and adjustable inlet pressure loss. A 3m immersion heater (capable of up to 300kW/m2) forms the inner wall of the annulus test section and is directly upstream of a 2m unheated chimney section of the same geometry.
- The experimental data includes measurement of void fraction, temperature, pressure, and flow rate. Data are collected in 5 places along the test section.

Parameter	Value
Geometry	Vertical internally-heated annulus
Inner diameter [mm]	19.05
Outer diameter [mm]	38.1
Heated length [mm]	3000
Unheated length [mm]	2030
System Pressure [kPa]	145-950
Heater power [kW/m^2]	50-275 (max 300)
Inlet Loss Coefficient [-]	22-310

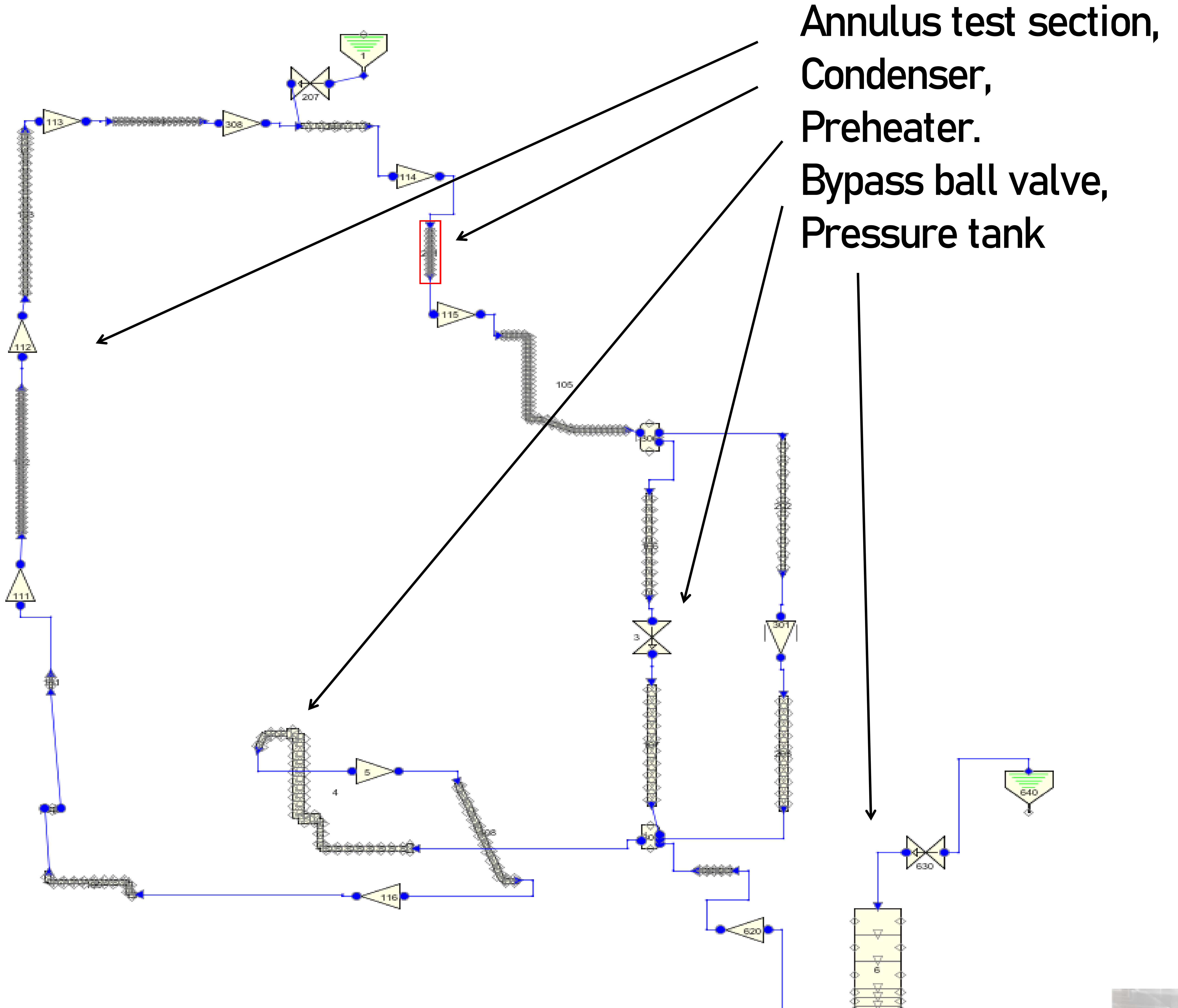


Schematic and picture of the test facility

A – Annulus test section, B-Condenser, C-Pump, D- Globe valve, E- Bypass ball valve, F- Pump isolation ball valve, G- Flowmeter, H- Preheater.
Pressure and temperature instrumentation location: 1.0- Anulus inlet, 1.1-1.5- Port-1 – Port-5 (additionally void fraction and gas velocity measured), 2- Condenser inlet, 3- Condenser outlet, 4-Return outlet, 5-Preheater exit

Model and nodalization

- **RELAP5** (*The Reactor Excursion and Leak Analysis Program*) computer code is a light water reactor transient analysis code developed for the U.S. Nuclear Regulatory Commission, NRC
- The Symbolic Nuclear Analysis Package SNAP was used to assist the modelling of the natural circulation loop.
- Model consists of pipes, branches, single junctions and volumes, time dependent volumes and junction components.
- Additionally the heated part (pipe 102) of the test section and condenser (pipe 201) are covered by heat structure.



Model nodalization

Experiments conditions

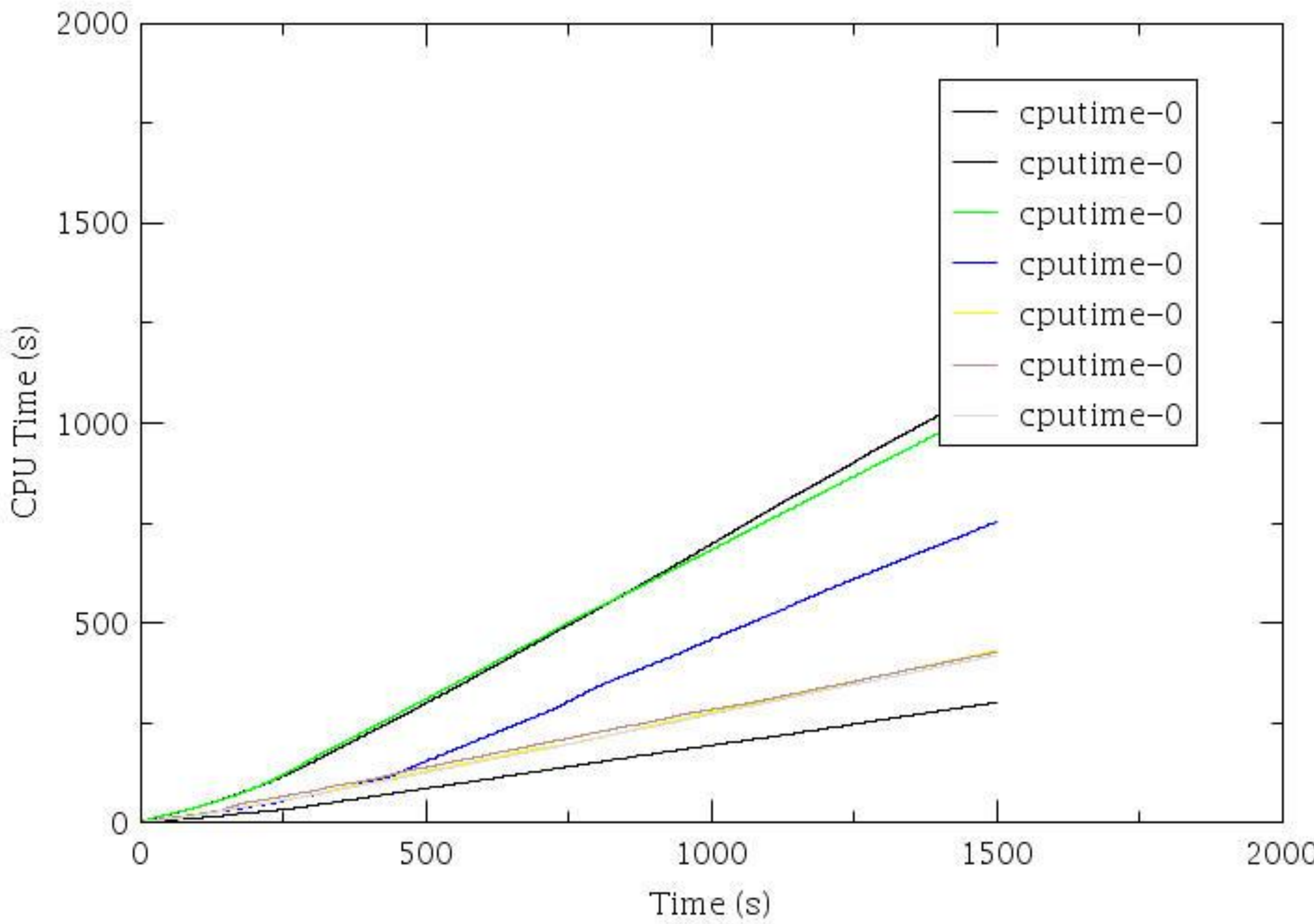
- **Initial Conditions**
  - All volumes (in pipe and branch components) are specified for initial conditions by temperature and pressure.
  - For all junctions the initial mass flow rate is set as 0.24kg/s.
  - The simulation runs for 1500s.
- **Boundary Conditions**
  - **For natural circulation conditions the mass flux is not an independent control parameter but the consequence of the natural circulation flow**. Mass flux depends on four Boundary Conditions:
    - inlet loss coefficient K-loss which can be adjusted by a globe valve position,
    - pressure of the system (pressure tank)
    - inlet subcooling (condenser) and
    - heat flux (power) – for stability convergence power will increase from 0 to desired value in 200s.
  - Those parameters were in different configuration for 107 experimental conditions and the range of them is specified in the table. Specific data in [1]

Parameter range

Parameter	Value
System pressure	145-950 kPa
Inlet subcooling	6-48°C
Heat flux	50-275 kW/m2
Inlet loss coefficient	22-310
Mass flux	180-590 kg/m2-s

Code and hardware version

- Code version: RELAP5/3.3km (July 2016), /MOD3.3Patch05
  - **relap5-m33p5(km)-win32-ifc-opt-b2-snap**
  - Windows 7 Pro 64bit / IFC 13.1 /c /O1
- Hardware: The code was run on a 64-bit Windows 10, laptop machine equipped by the Intel(R) Core(TM) i7-6700HQ CPU 2.6 GHz, 32 GB RAM.
- On Figure CPU time needed for simulation is presented, in the function of simulated steady state time. Times can vary depends on the boundary conditions from 300 up to 1300s.

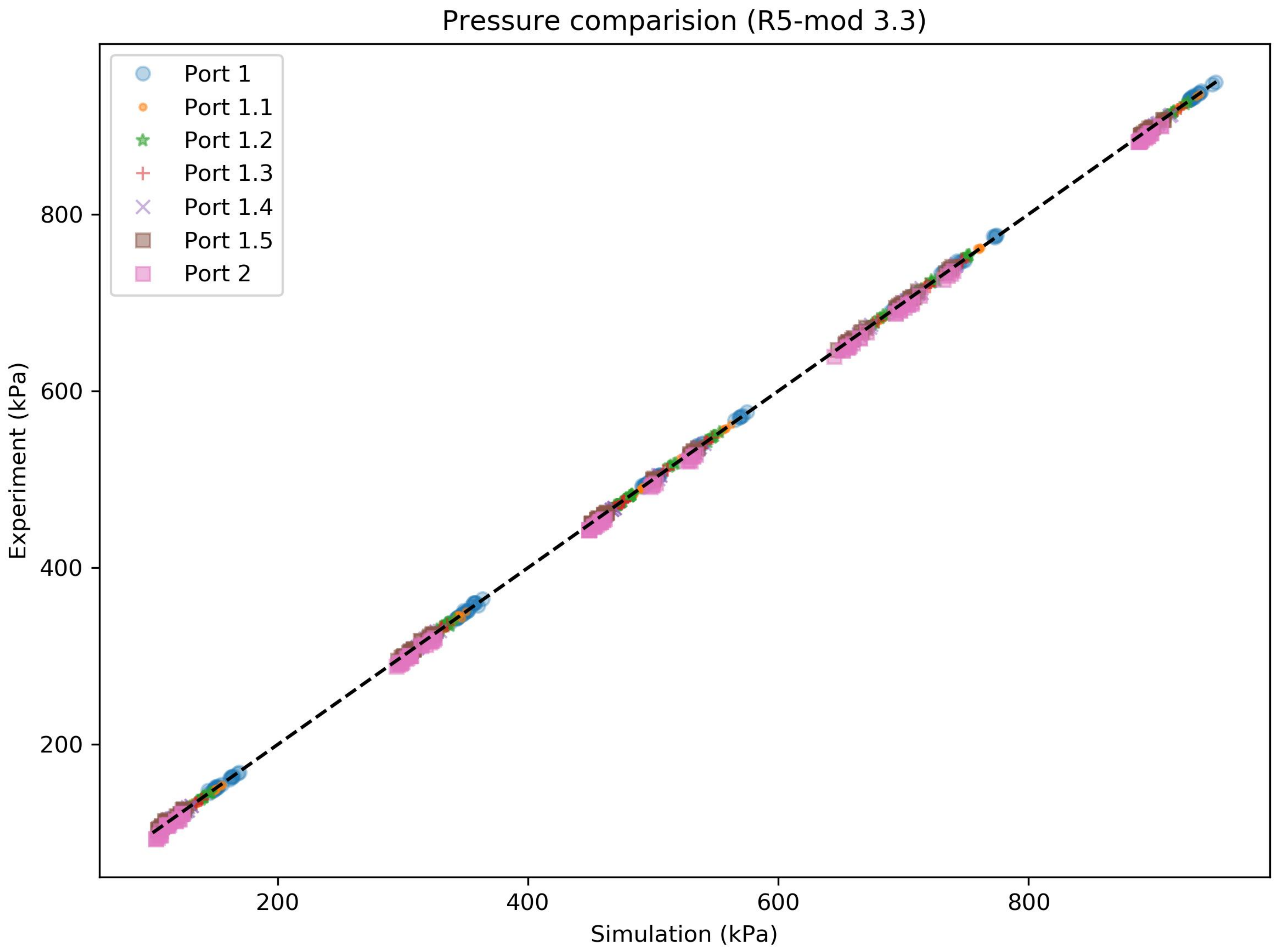


CPU time of the simulations

Results – non oscilation conditions

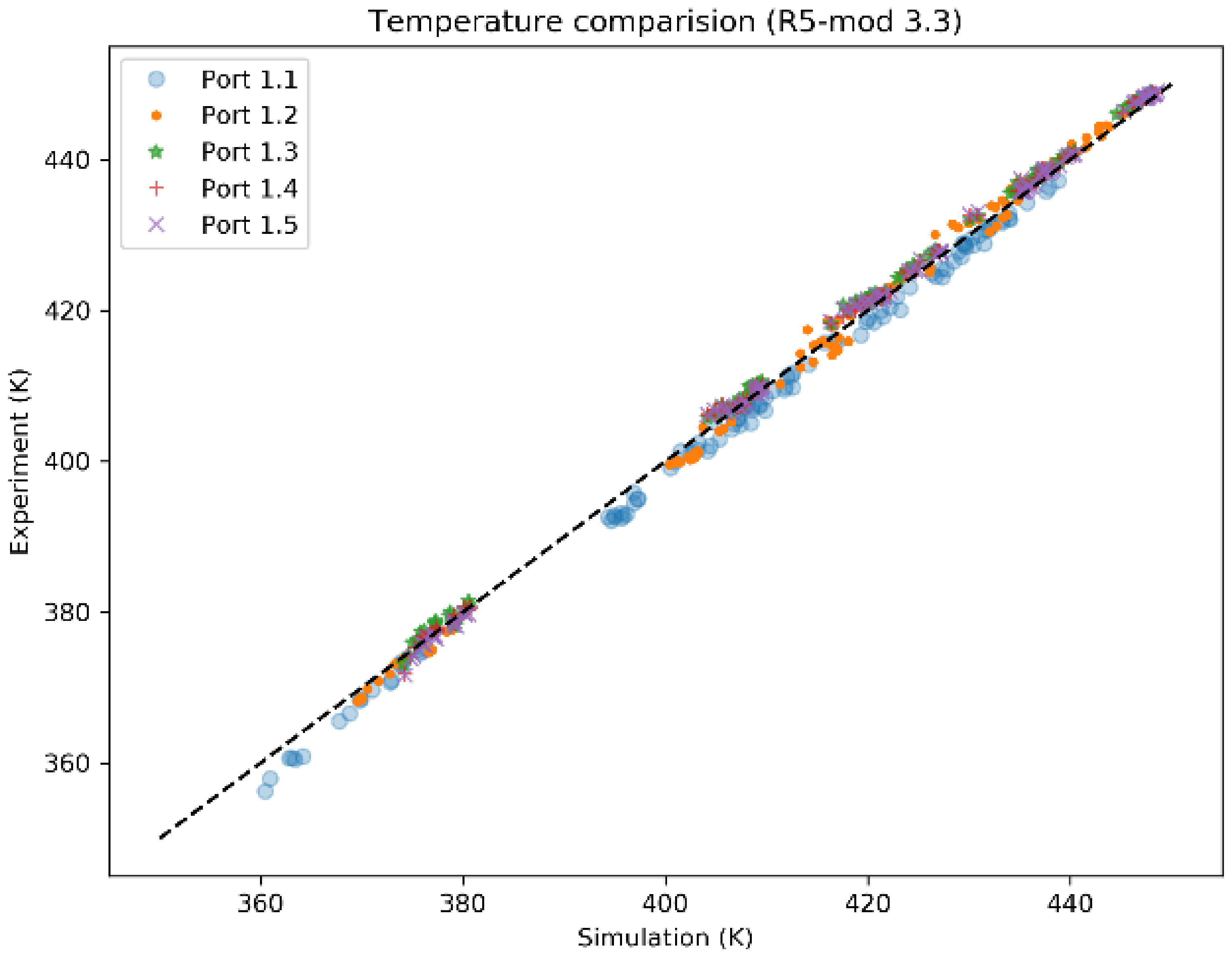
All 107 cases were calculated with different boundary and initial conditions described in [1]. According to the predictions some cases at low pressure met the oscillation (numerical). Most of the cases were very stable (without oscillations) and reflect in a good agreement the experimental data.

Case No	Pressure range
1-19	145-168kPa
20-40	350-360kPa
41-66	500-570kPa
67-91	695-775kPa
92-107	930-950kPa

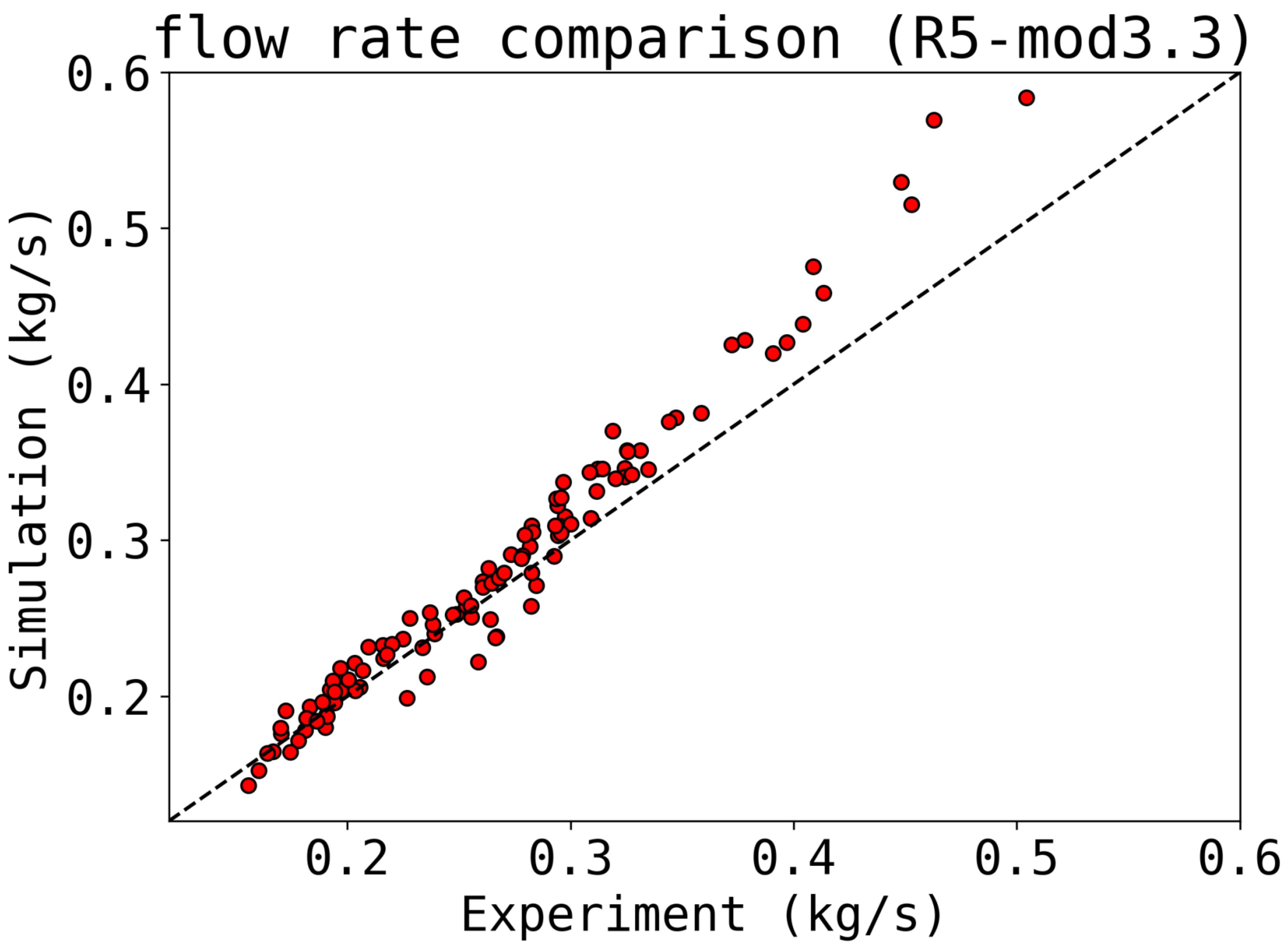


Pressure comparison

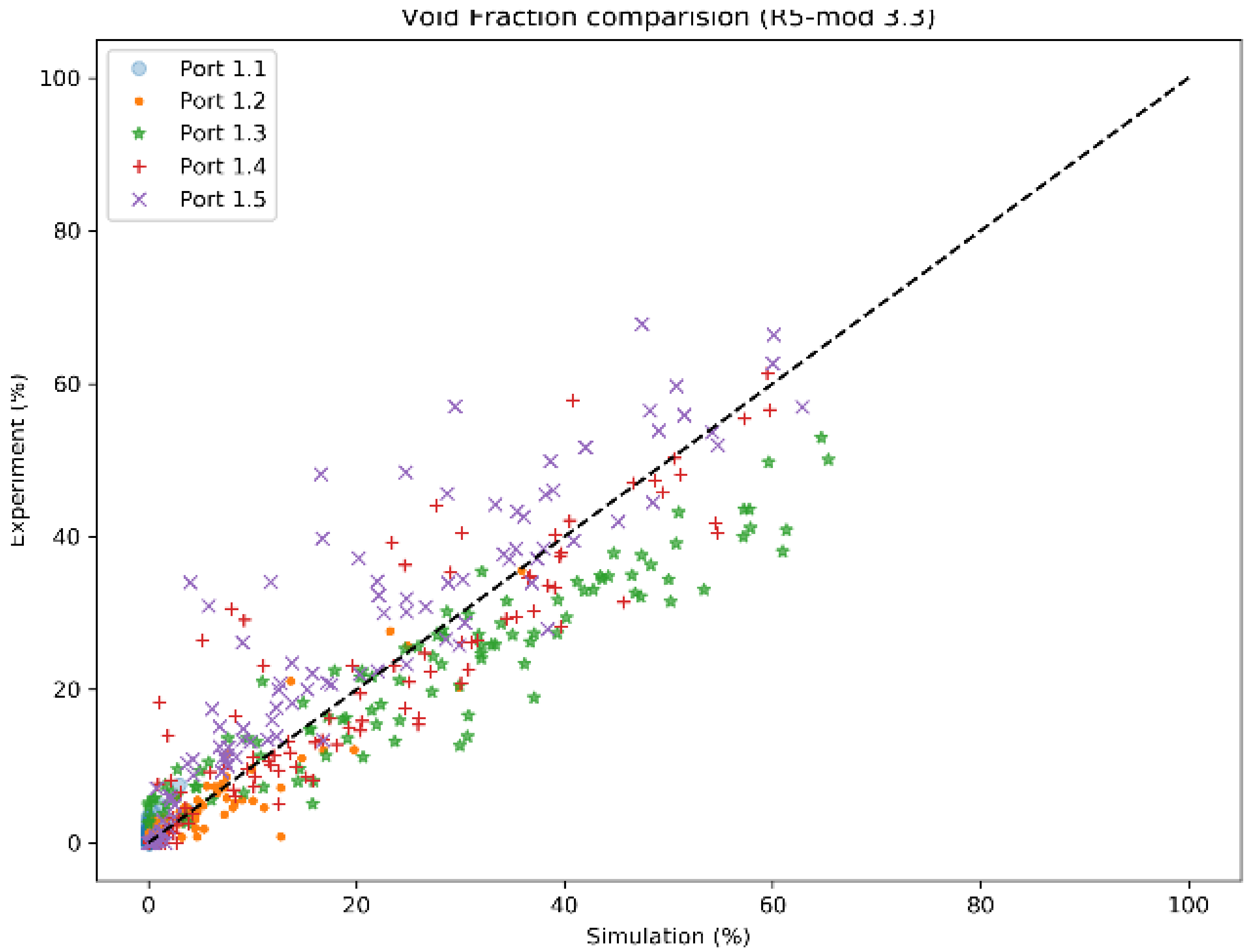
Temperature comparison

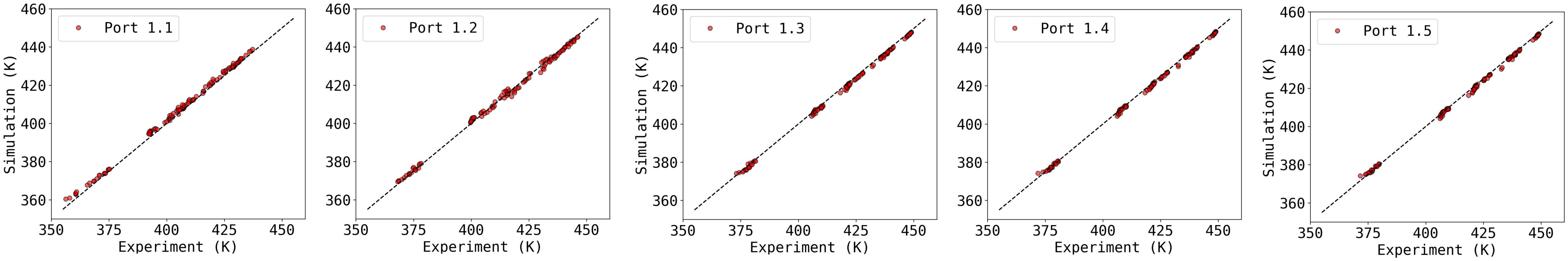


Flow rate comparison



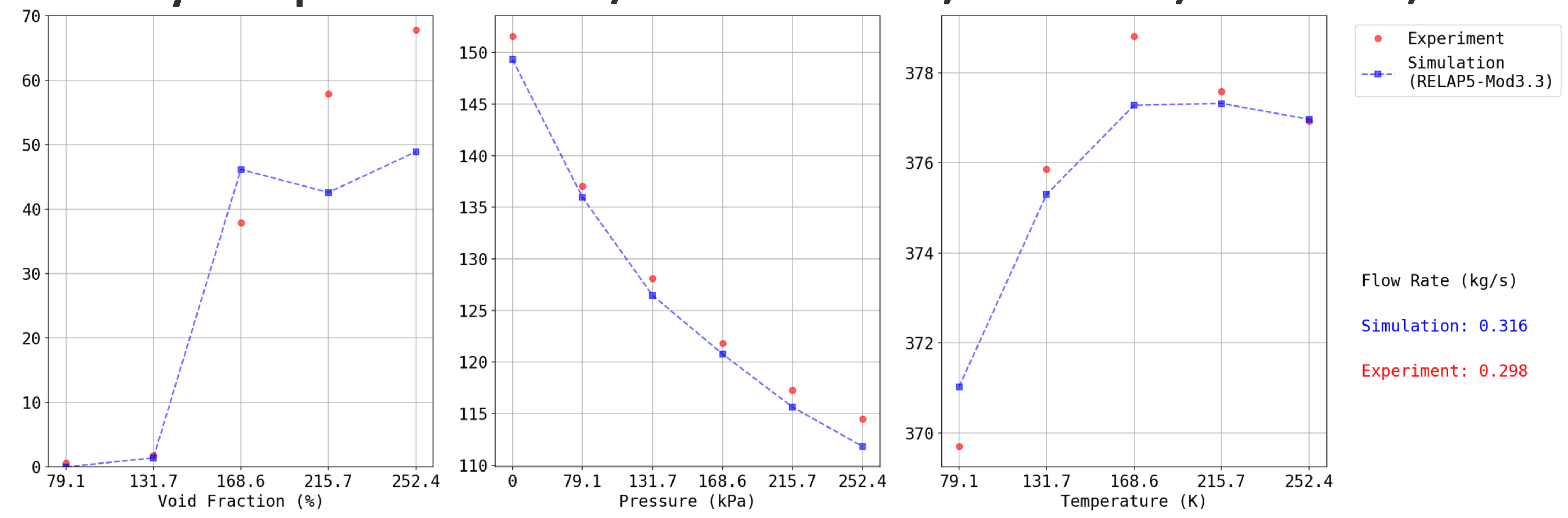
Void fraction comparison



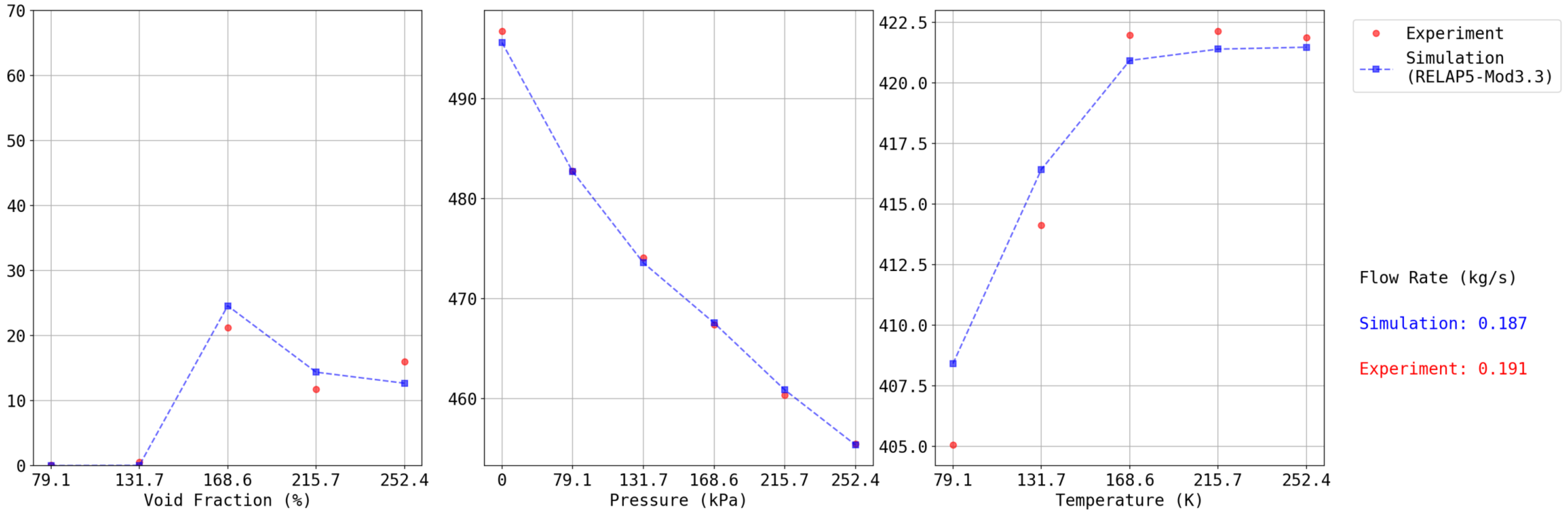


Temperature comparison, ports separated

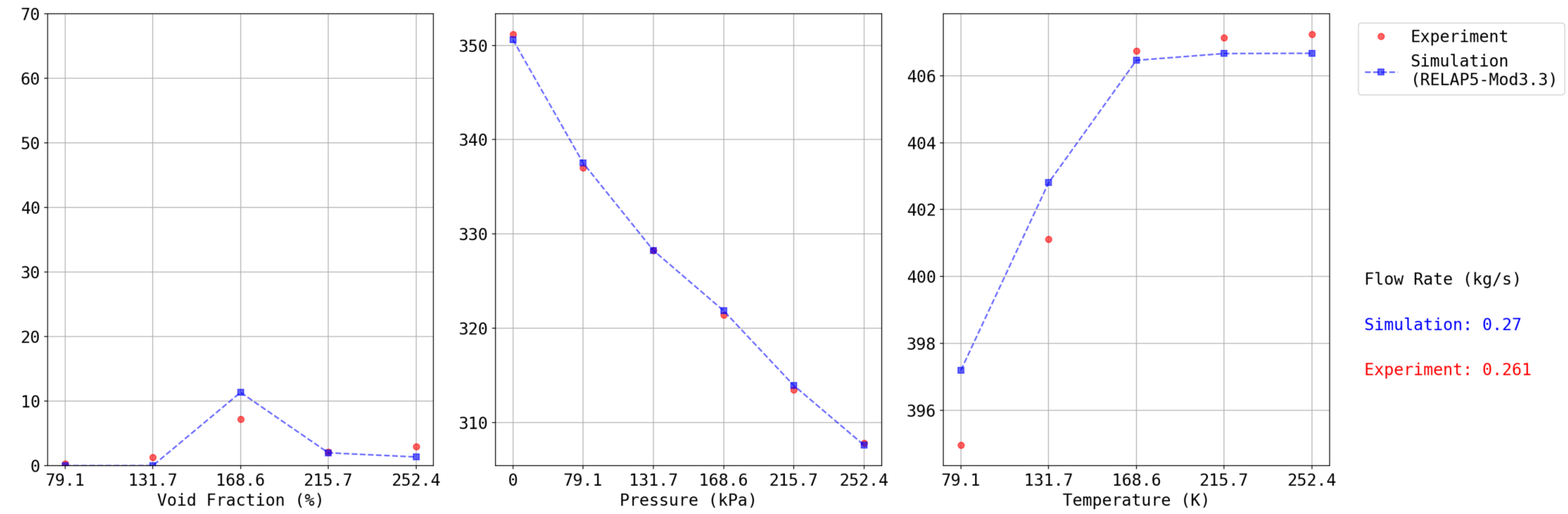
Figures below present the void fraction, pressure and temperature measured in characteristic ports of facility at positions z/Dh = 79.1 / 131.7 / 168.6 / 215.7 / 252.4 and show corresponding calculation data



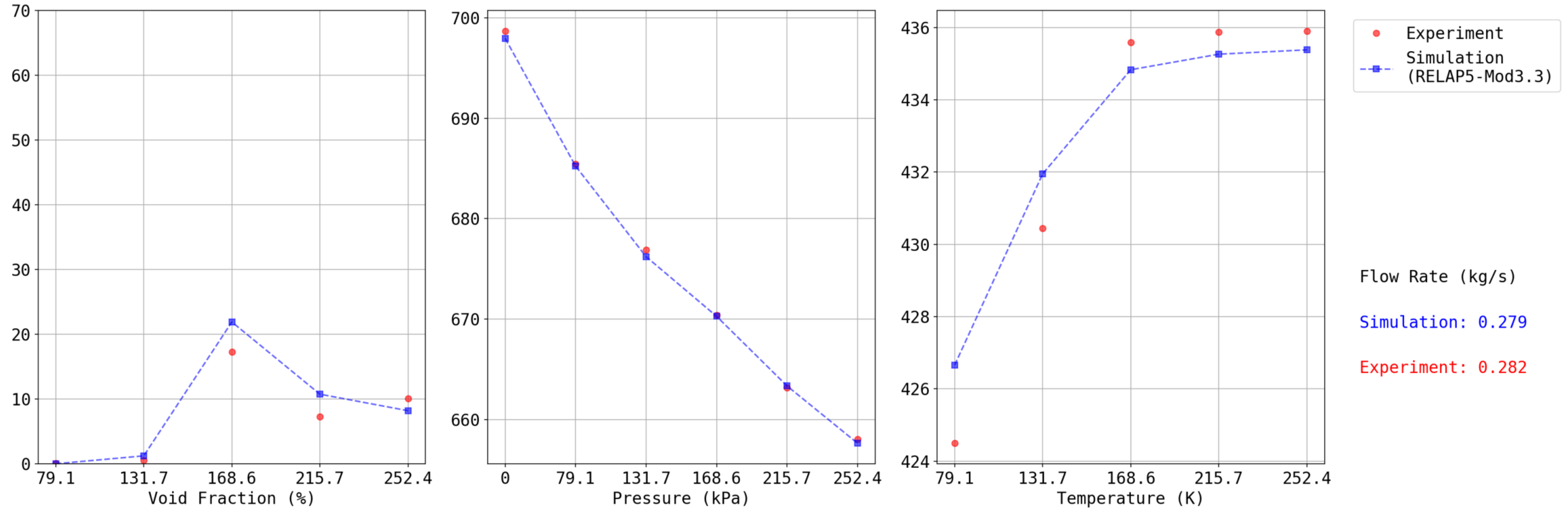
153kPa_4.8GPM_20.4C_60%_8R



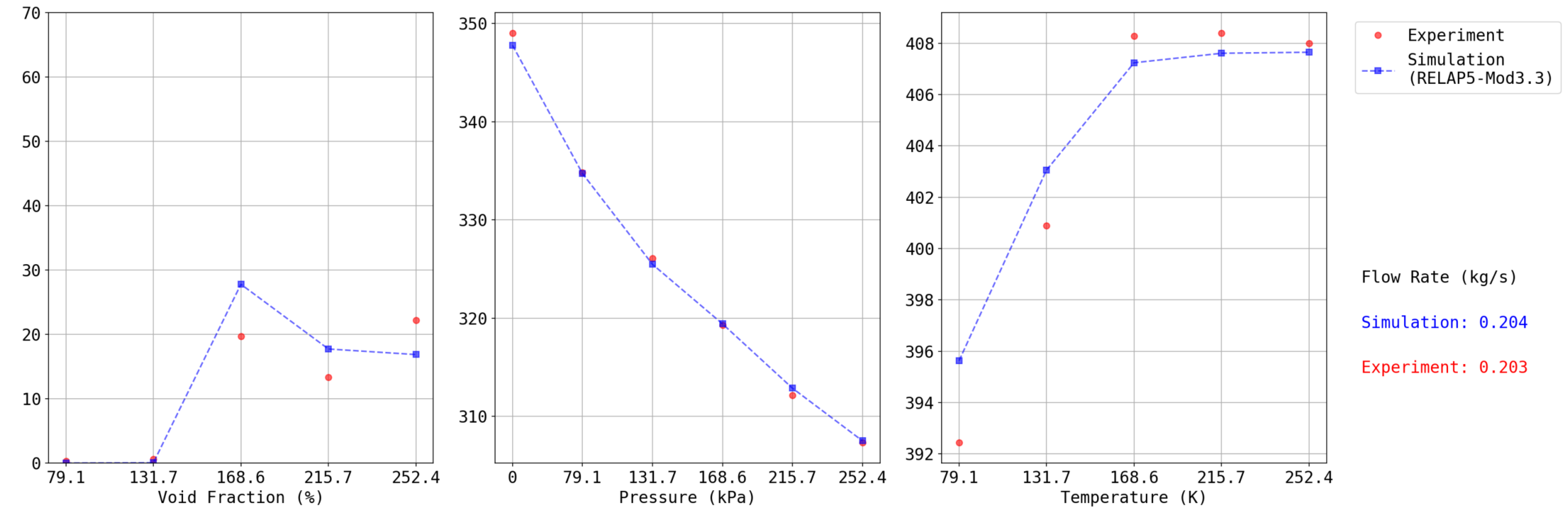
499kPa_3.2GPM_27C_65%_8R



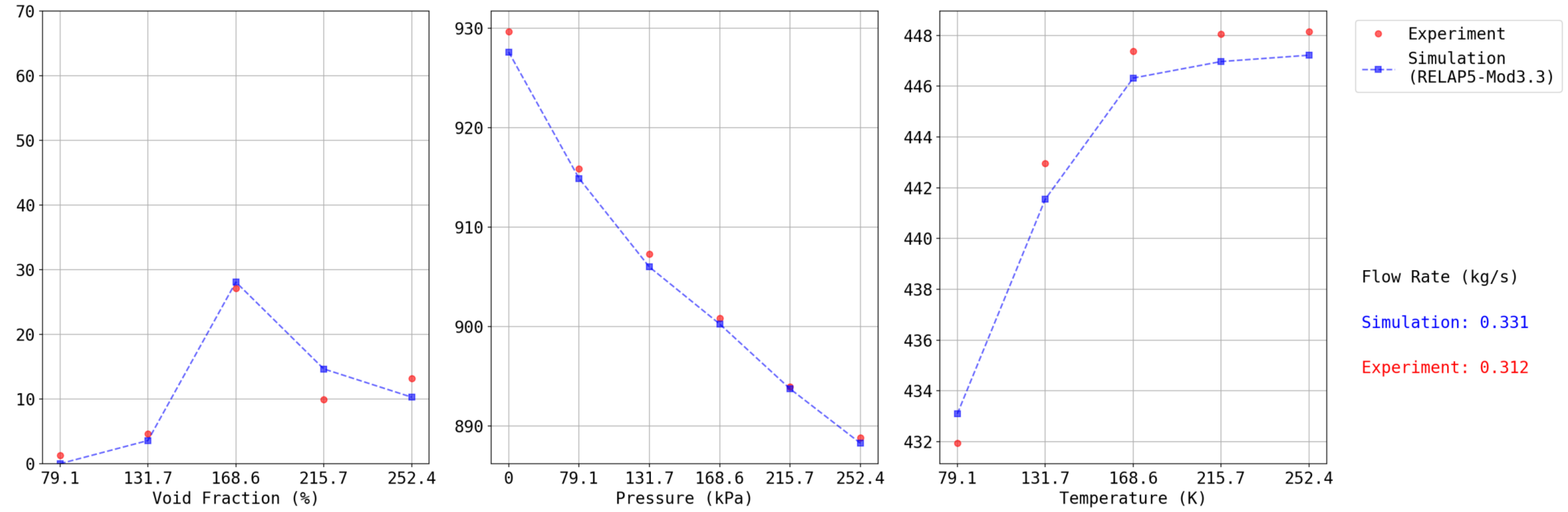
353kPa_4.75GPM_22.5C_65%_6R



700kPa_4.8GPM_17.7C_65%_7.5R



351kPa_3.4GPM_26.7C_65%_8R



933kPa_5.4GPM_28.5C_90%_7.5R

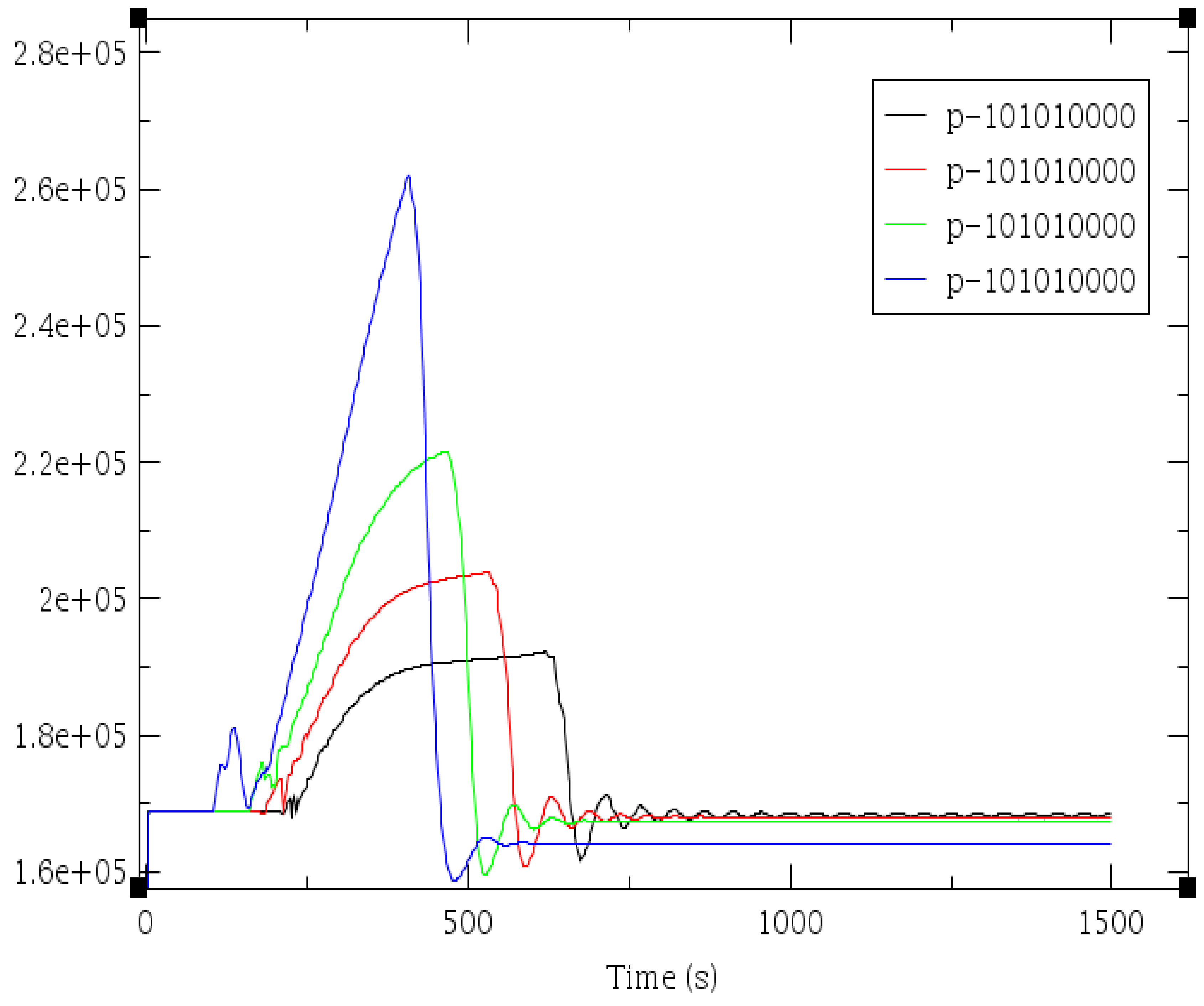
Sensitivity analysis – parameter study

- For some unstable cases the periodical oscillations were observed. Especially low pressure conditions around 150kPa. Parameter study was performed on the example of K-loss coefficient.
- Change of the pressure losses influences the flow conditions and *introduce* or *limit* the oscillations in the flow.
- Sensitivity study has been performed for K_loss in following range:
  - 22.10
  - 45.50
  - 89.90
  - 310.50

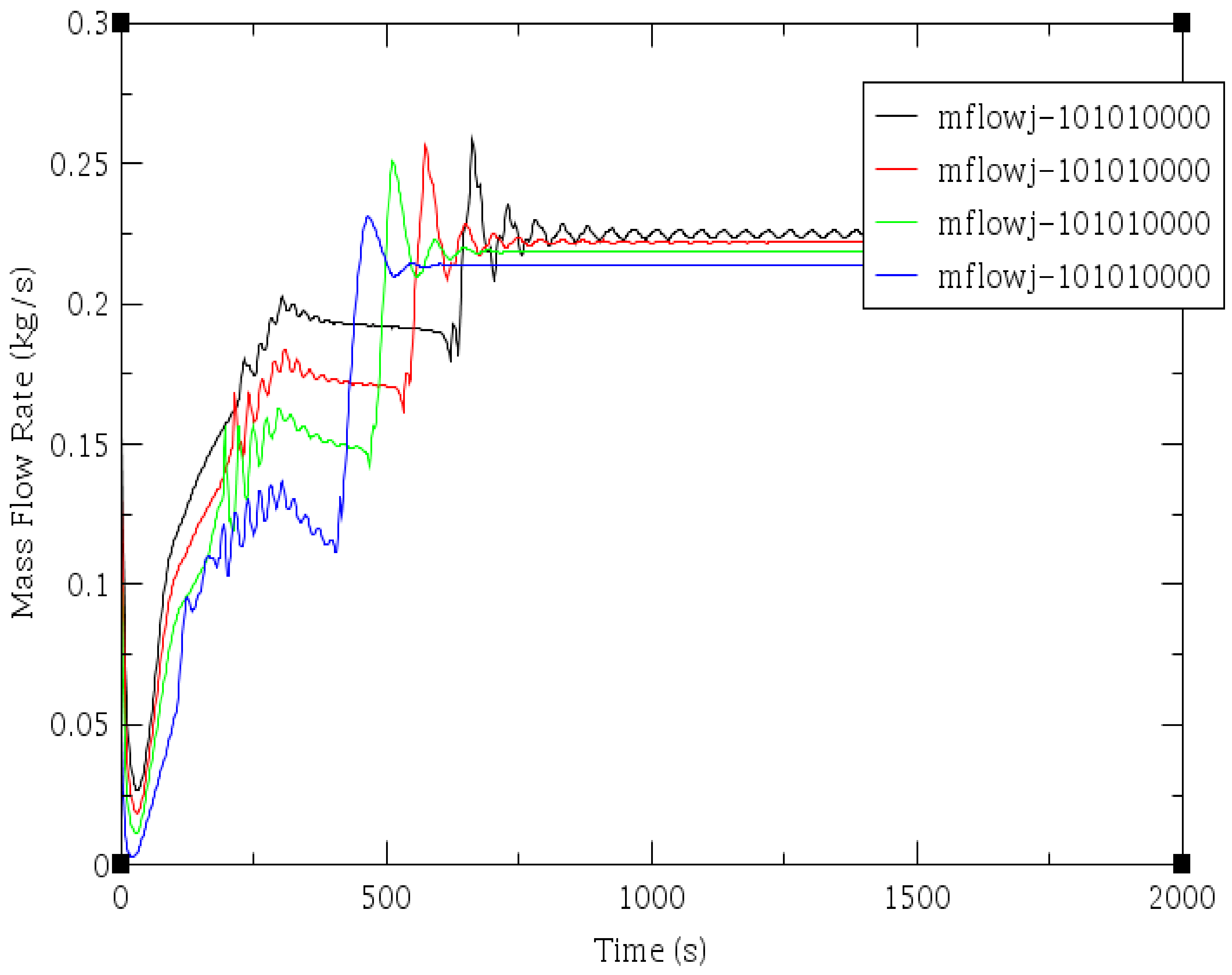
Parametric study

Boundary conditions for this unstable case:

Pressure: 168.16kPa, *Heat flux*: 58.74 kW/m2, *Inlet subcooling*: 19.69K, *Mass flux*: 306.3 kg/m2s, *K_loss*: 22.11



22.10
45.50
89.90
310.50



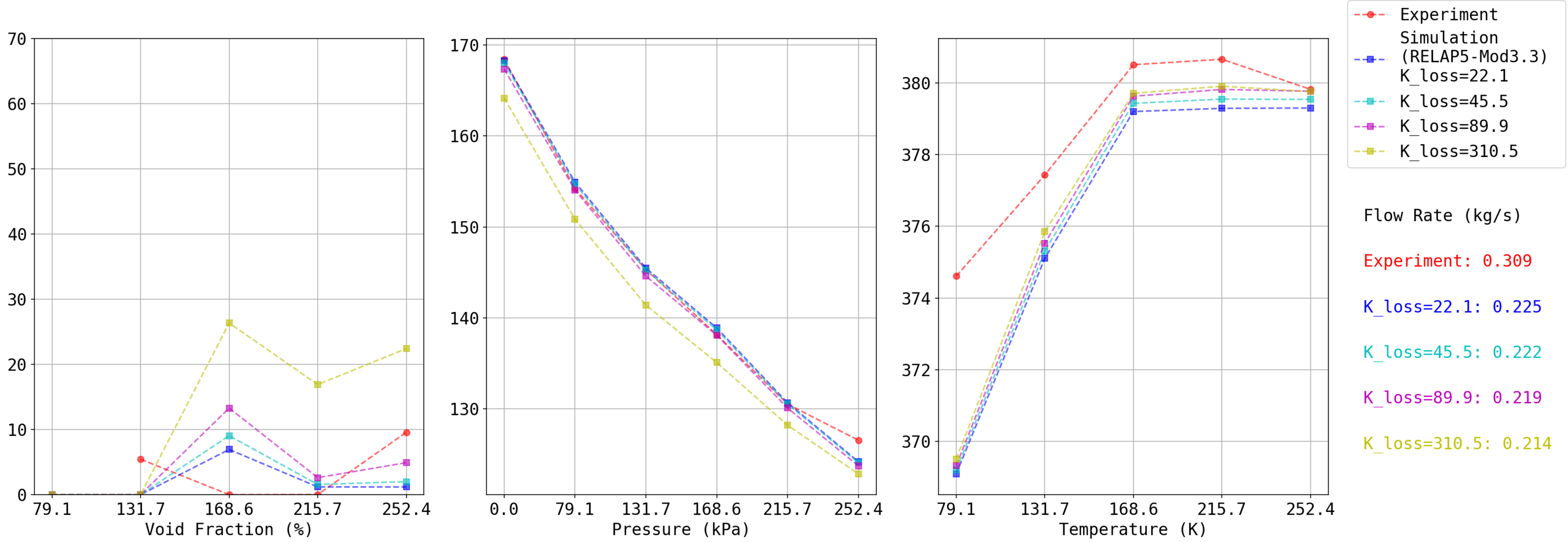
22.10
45.50
89.90
310.50

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

Parametric study

Boundary conditions for this unstable case:

Pressure: 168.16kPa, *Heat flux*: 58.74 kW/m2, *Inlet subcooling*: 19.69K, *Mass flux*: 306.3 kg/m2s, *K_loss*: 22.11



Flow Rate (kg/s)

Experiment: 0.309

K_loss=22.1: 0.225

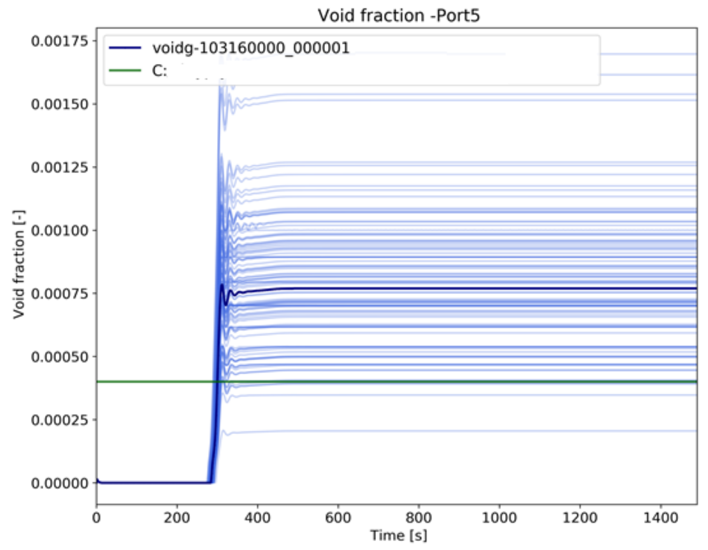
K_loss=45.5: 0.222

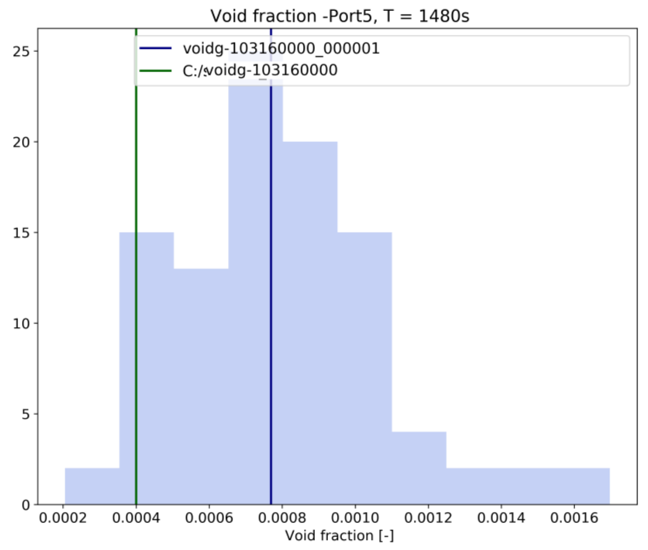
K_loss=89.9: 0.219

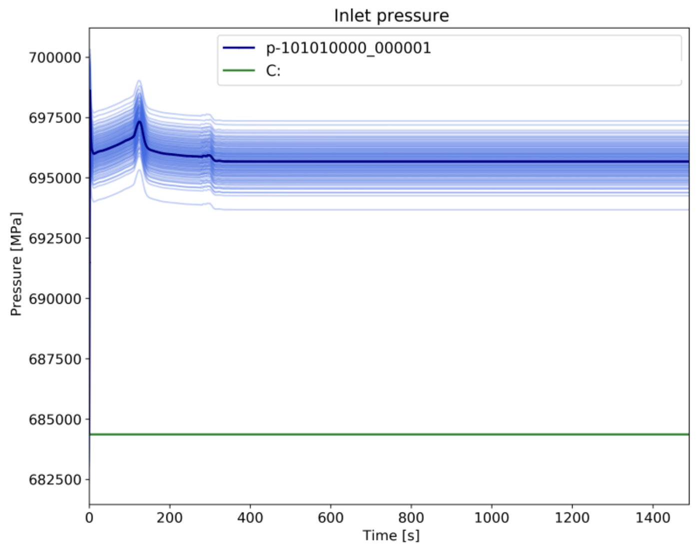
K_loss=310.5: 0.214

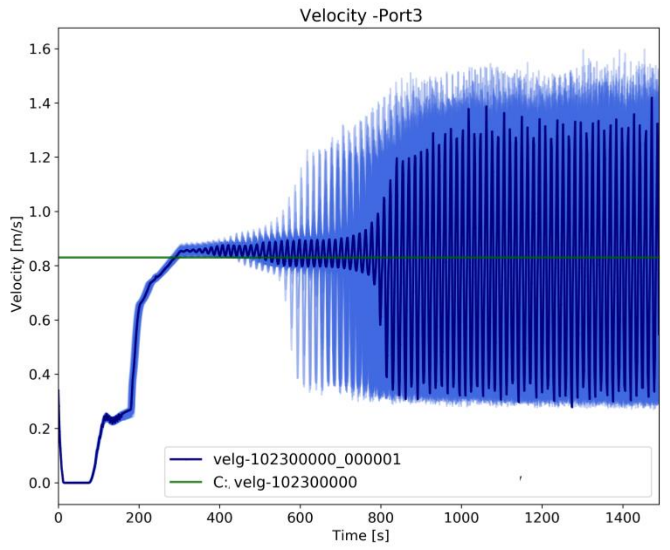
Conclusion and future plan

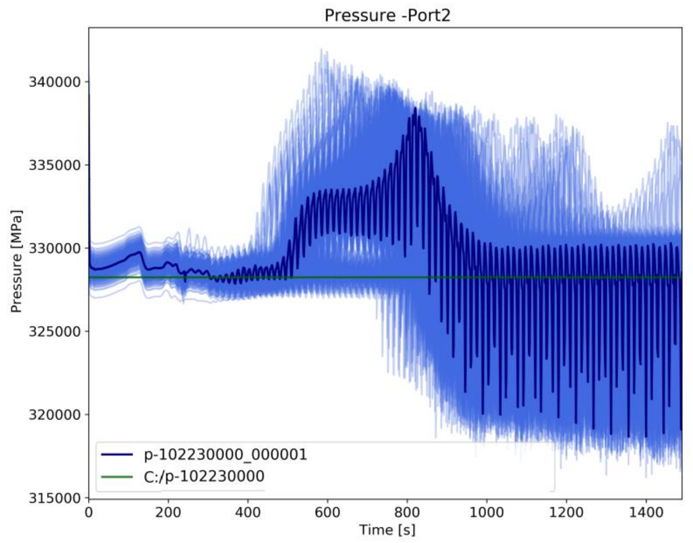
- Main experimental measurements of void fraction, pressure, temperature and flow rate were compared for different positions of the test section with RELAP5 mod 3.3 simulation.
- Results of simulations are in good agreement with the experiment, however, some experiements were performed under periodic oscilations (especially with low system pressure level).
- The performed calculations demonstrate that RELAP5 code can successfully describe the flashing process in the natural circulation system.
- In unstable flows the capability of RELAP5 to capture the oscillation period and amplitude is promising but may require improved constitutive relations for vapor generation
- Some uncertainty analysis needs to be performed with the code to consider the uncertainty in the measured boundary conditions and to assess (predict) the stability criteria for unstable flows.











References

[1] C.S., Ooi, Z.J., Kumar, V., Zou, L., Kozlowski, T., Golchert, B., Brooks. Validation of RELAP-7 for Forced Convective and Natural Circulation Reactor Flows: Task 2.1 Two-phase natural circulation data for validation of system analysis code. Technical Report, Project ID: DOE-16-10630, Milestone ID: M2NU-16-IL-UIUC-030401-065., 2018.

[2] T. Zhang, Z.J. Ooi, M. Skrzypek, C.S. Brooks, Int. J. Heat Mass Transfer, Vol. 151 (2020) 119447, A multi-dimensional dataset for two-phase instability in low pressure natural circulation based on direct transient local measurement

Questions?

maciej.skrzypek@ncbj.gov.pl

NARODOWE
CENTRUM
BADAŃ
JĄDROWYCH
ŚWIERK