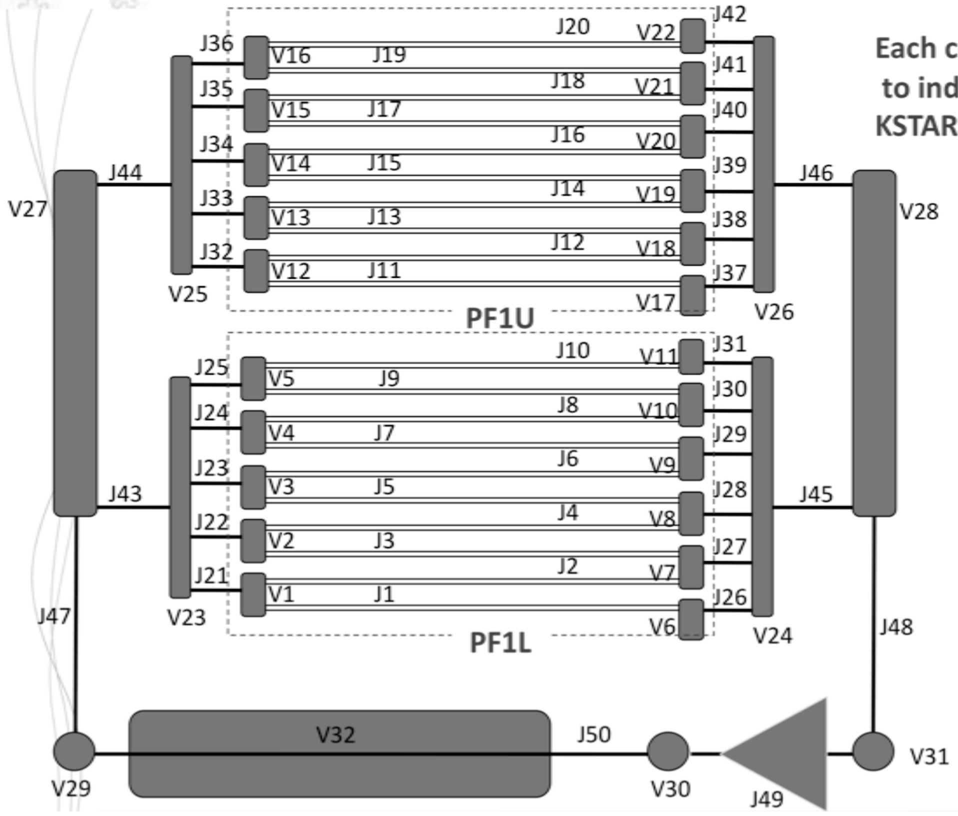
Modeling the KSTAR PF magnet system

Dong Keun Oh, Sangjun Oh

1. SUPERMAGNET model of the KSTAR magnet
2. Attempt to improve the cryo-network solver
3. Plenum model and flux boundary condition
4. Test runs of the experimental components
5. Conclusion and discussion

SUPERMAGNET model of the KSTAR magnet

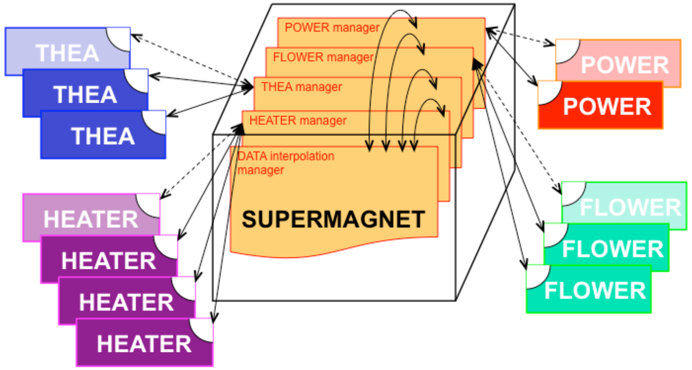


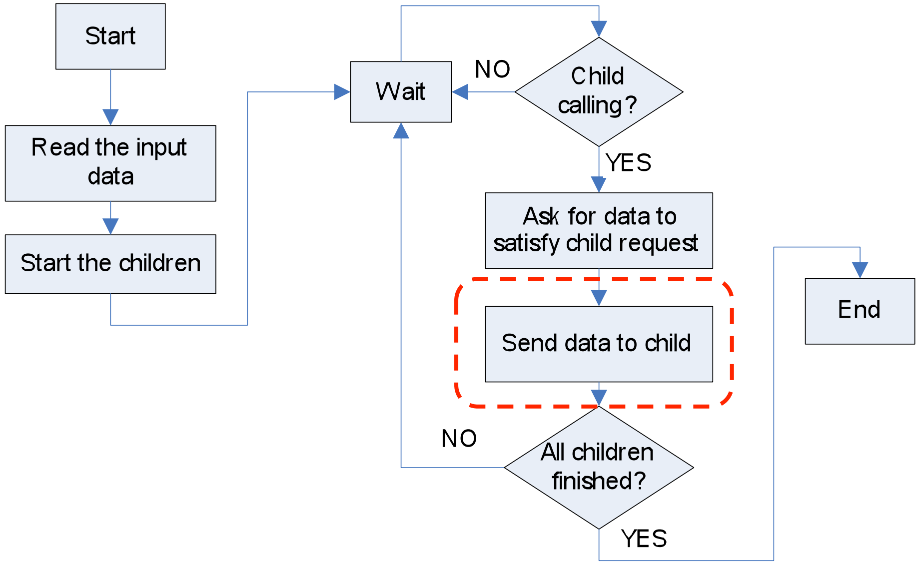
Each conductor line is coupled to individual THEA model of KSTAR CICC

J1-J20 : PF1UL CICCs (20)
J21-J25 : PF1L inlet pipes (5)
J26-J31 : PF1L outlet pipes (6)
J32-J36 : PF1U inlet pipes (5)
J37-J42 : PF1U outlet pipes (6)
J43 : PF1L supply feeder line (1)
J44 : PF1U supply feeder line (1)
J45 : PF1L return feeder line (1)
J46 : PF1L return feeder line (1)
J47-J48 : supply and return
cryolines (2)
J49 : circulation pump (1)
J50 : HX line (1)

Note)

SUPERMAGNET – a dotted line approach of integrated simulator…
: <u>a master (orchestration) code</u> written in programming language





- **Orchestration of individual solvers written in Fortran + C**
- **Distribution in source code – mostly Fortran 77**
- **Unix native data communication (pipe and signal)**
- **Implicit and linearized scheme for the hydrothermal solver**

The master code engages interprocess communication using pipe (UNIX-native).

L. Bottura, SuperMagnet benchmarking close-out meeting
ITER-IO Cadarache , 15th May, 2012

Engineering works for the magnet operation in KSTAR

1. **The ultimate goal is to develop an accurate model of the KSTAR magnet for real-time application.**

   - Zerodee (0-D) model has been tested as an ad-hoc approach.

   - Feasibility of real-time application is done using GPU

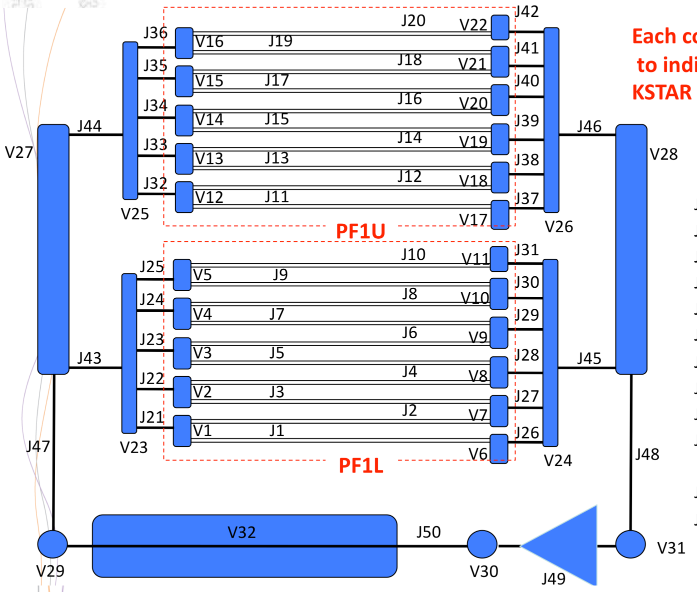
   - An idea→ implementing the parametric coupling
   : 0-D physical response + { convective-conductive coupling
   of empirical parameterization

2. **Such a simplified model should be assessed by a good simulator based on physical property of the magnet cryo-network.**

   - Development of full-scale PF model is an essential part.

   - R&D issues with SUPERMAGNET model.

SUPERMAGNET model – a pilot of the PF simulator



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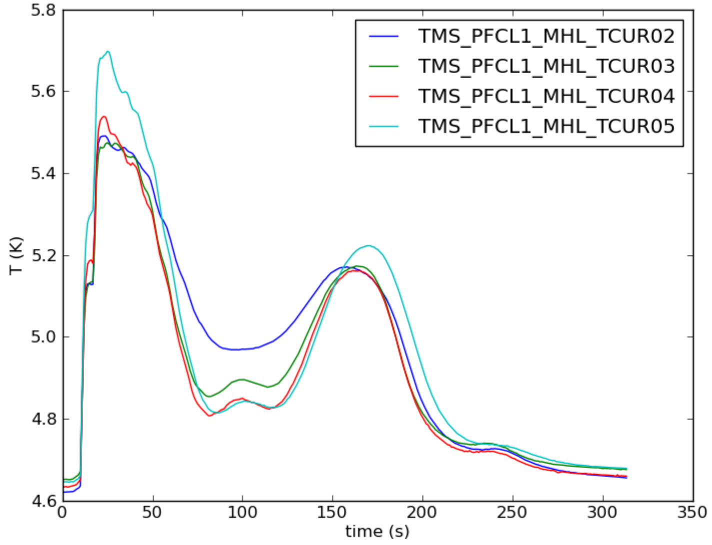
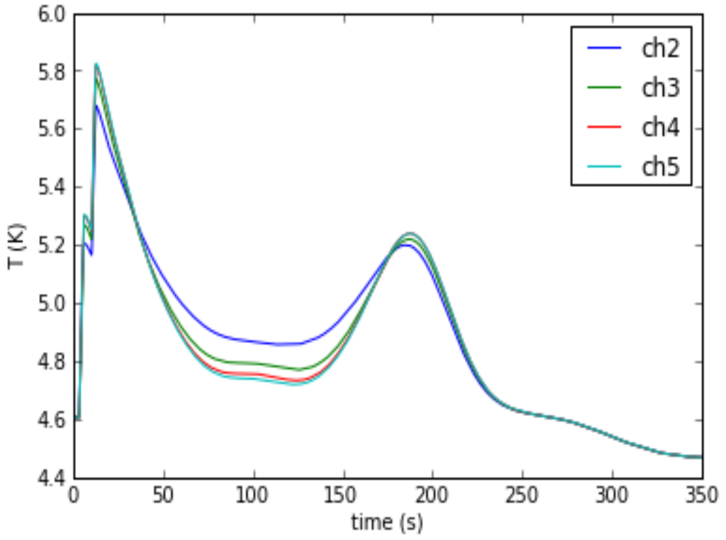
- A sub-network of the **PF magnet** loop
  : **PF1U + PF1L** with simplified circulation pump and HX
- **20 CICCs** are included in the model
  : one THEA process per each hydraulic channel (cable annulus) and cable → **20 THEA processes**
- Each boundary of 1-D conductor model was coupled to the volume nod in the hydraulic network model of helium circulation → **1 FLOWER process**
- **20 THEA** models + **1 FLOWER** model is managed by **SUPERMAGNET** code

shot #6631 of the magnet test in 2013



SUPERMAGNET model of PF1U and PL



R&D issues

- ✓ **Numerical aspects**

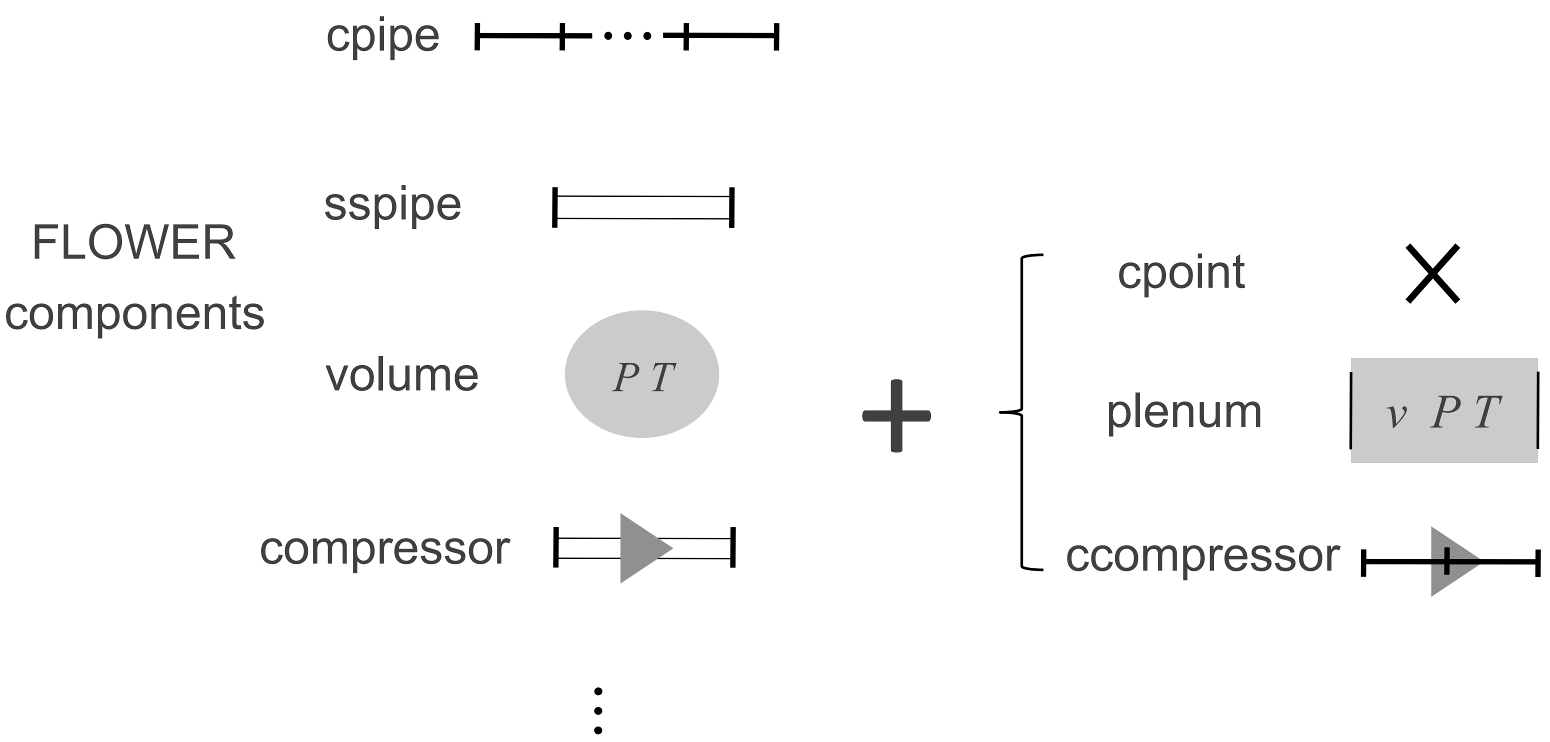
  : Numerical stability in the coupled boundary between the CICC model and general LHe flow network (FLOWER-THEA boundary)

- ✓ **Needs of practical component**

  : Modeling the circulation pump or active bi-pass networks

➔ So, a trial to resolve the issues with SUPERMAGNET has been attempted on the R&D activity.

Attempt to improve the cryo-network solver



FLOWER components

cpipe

sspipe

volume

compressor

+

cpoint

plenum

ccompressor

Motivation I

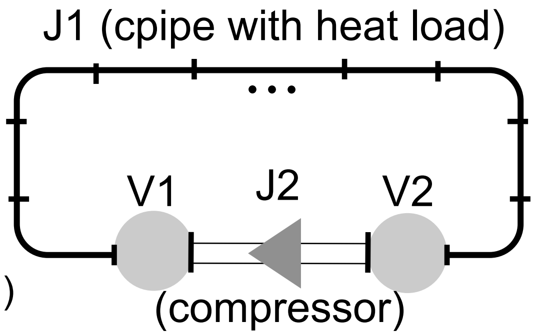
: FLOWER solves 1D flow assuming the physical boundaries as volumes (*i.e.* reservoirs of pressure and temperature)

- Let's look into the case :

J1 : 10 m (L), 1 mm (D)
J2 : 1 m (L), 1cm (D)

V1 & V2 : 0.001 cc

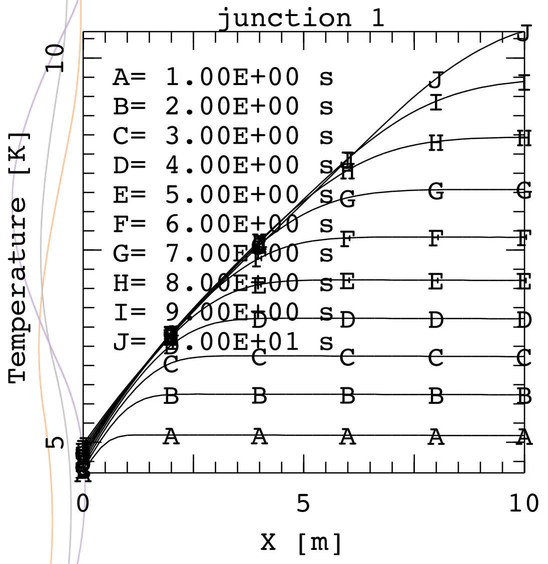
Heat load : 1 W/m,
(uniformly loaded to J1)

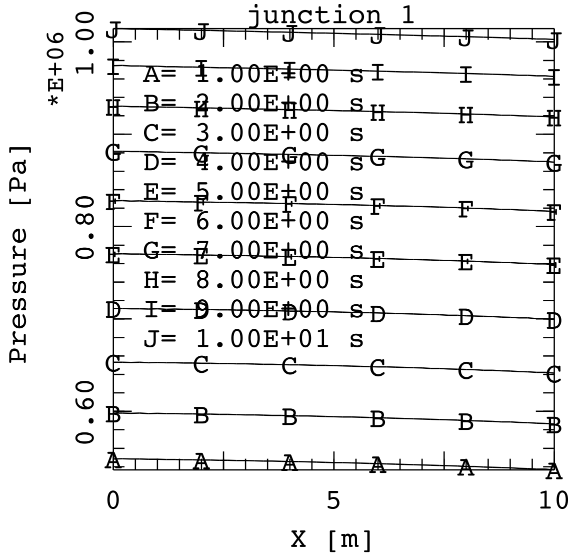


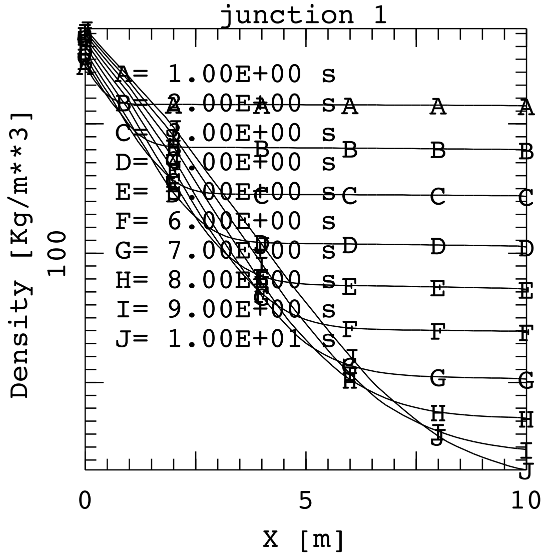
Pump : Δp_{max} = 0.015MPa
$\dot{m}_{max}$ = 1g/s

T_{init} = 4.5 K

P_{init} = 0.5 MPa

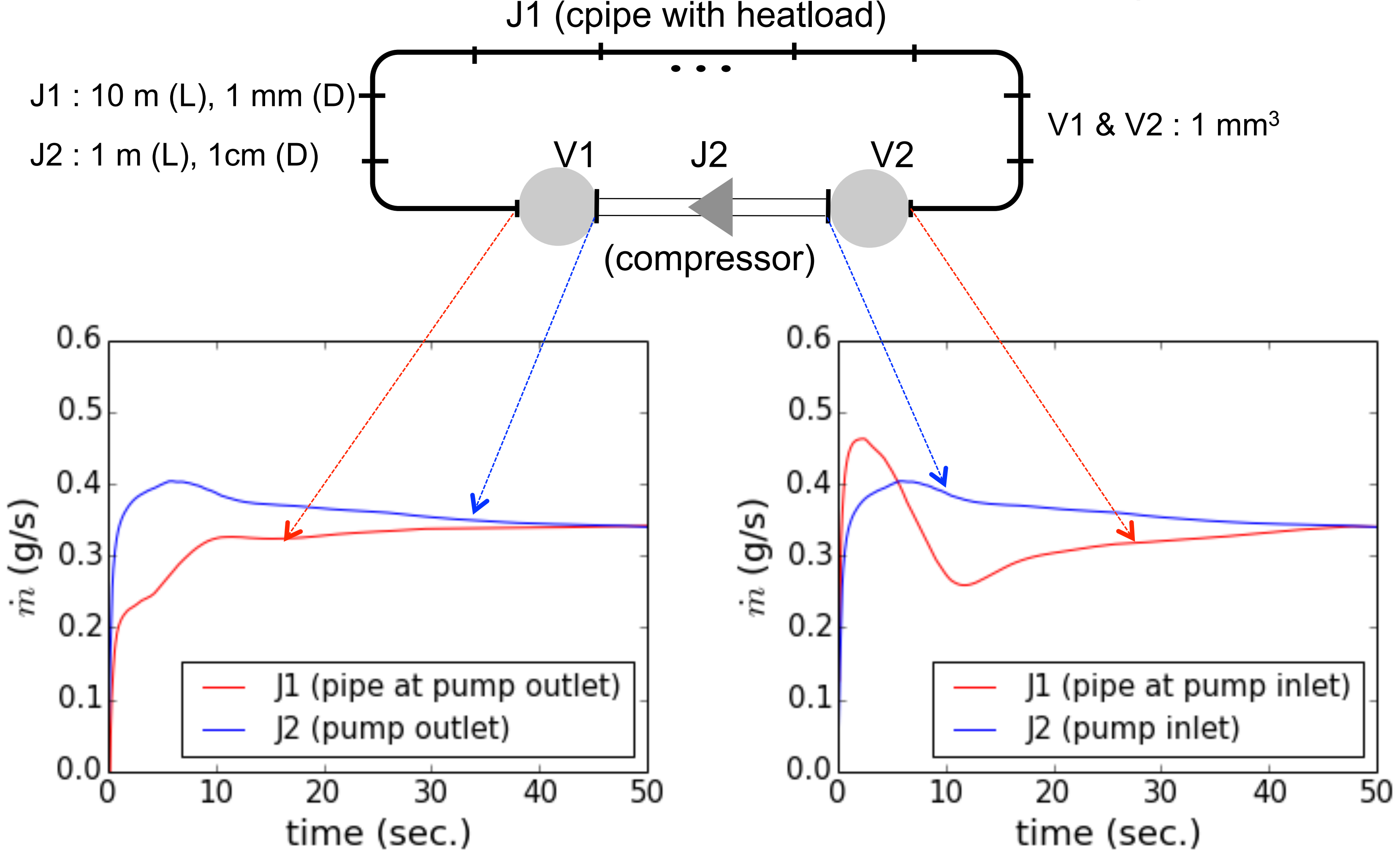






Motivation I (continued)

- Mass flow <u>discontinuity</u> crossing the volume → { unexpected behavior of the real-world's union coupler or reducer…



J1 (cpipe with heatload)

J1 : 10 m (L), 1 mm (D)

J2 : 1 m (L), 1cm (D)

V1 & V2 : 1 mm^3

V1

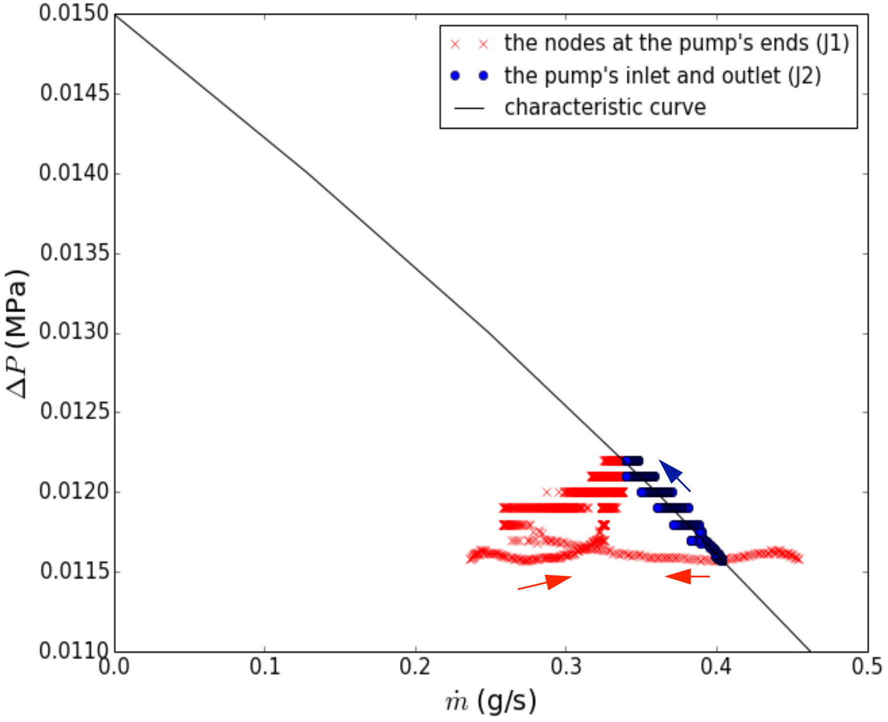
J2

V2

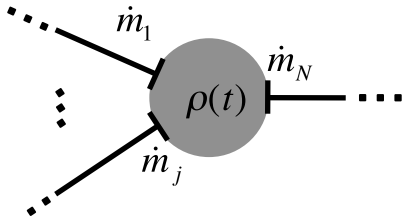
(compressor)

Motivation I (continued)

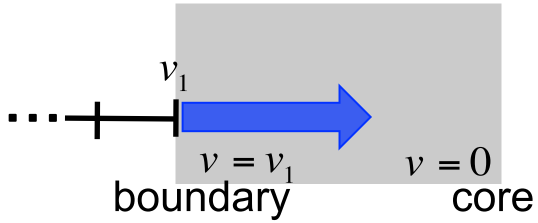
- The characteristic of compressor (pump) is distorted by the connection



- Mass conservation itself is consistent due to the change of density in volumes



- Free boundary assumption for the velocity is questionable, in case of small volume under rapid change of flow.



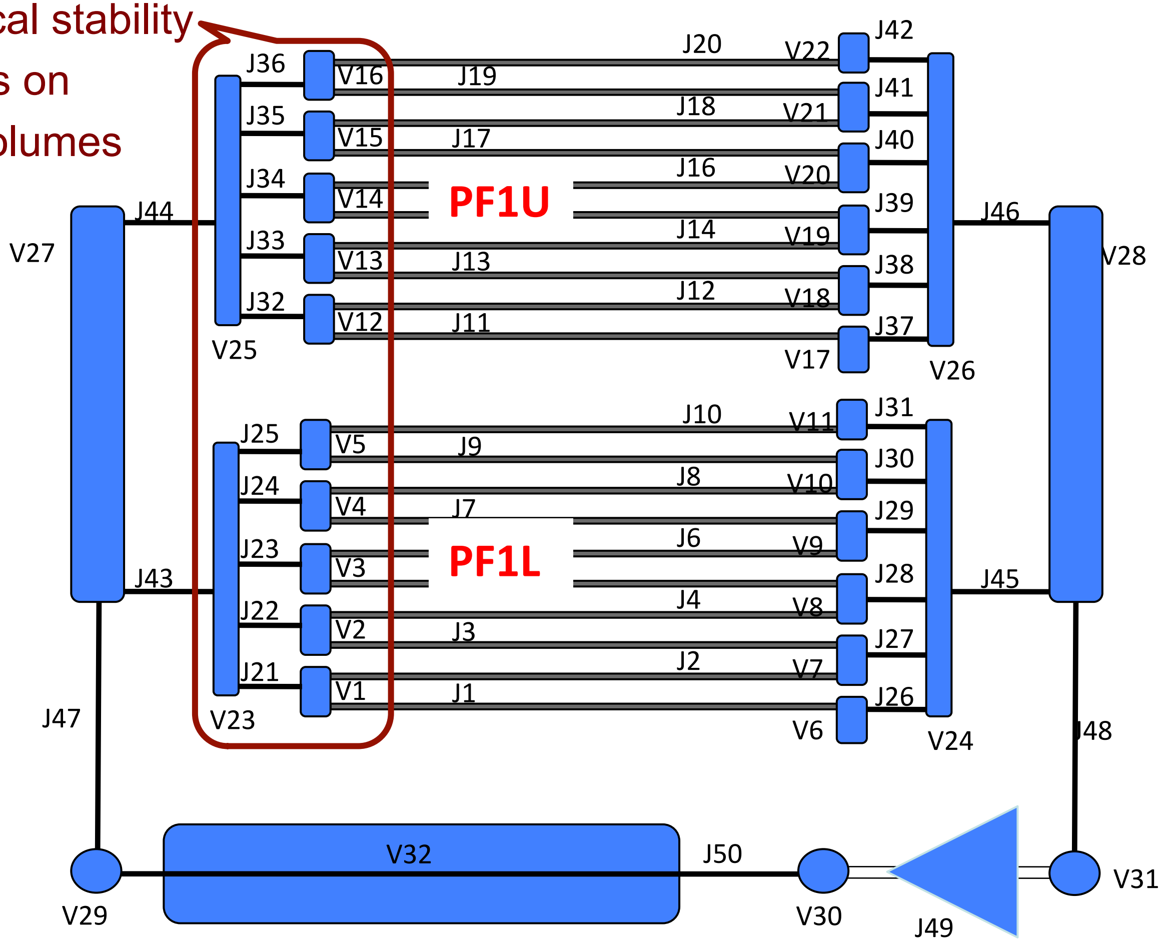
Motivation II

: With rapid time-varying flow, solution makes hard.

- The trouble depends on the size of volumes ;
  the larger volumes are, the easier solution converges.

Numerical stability depends on those volumes

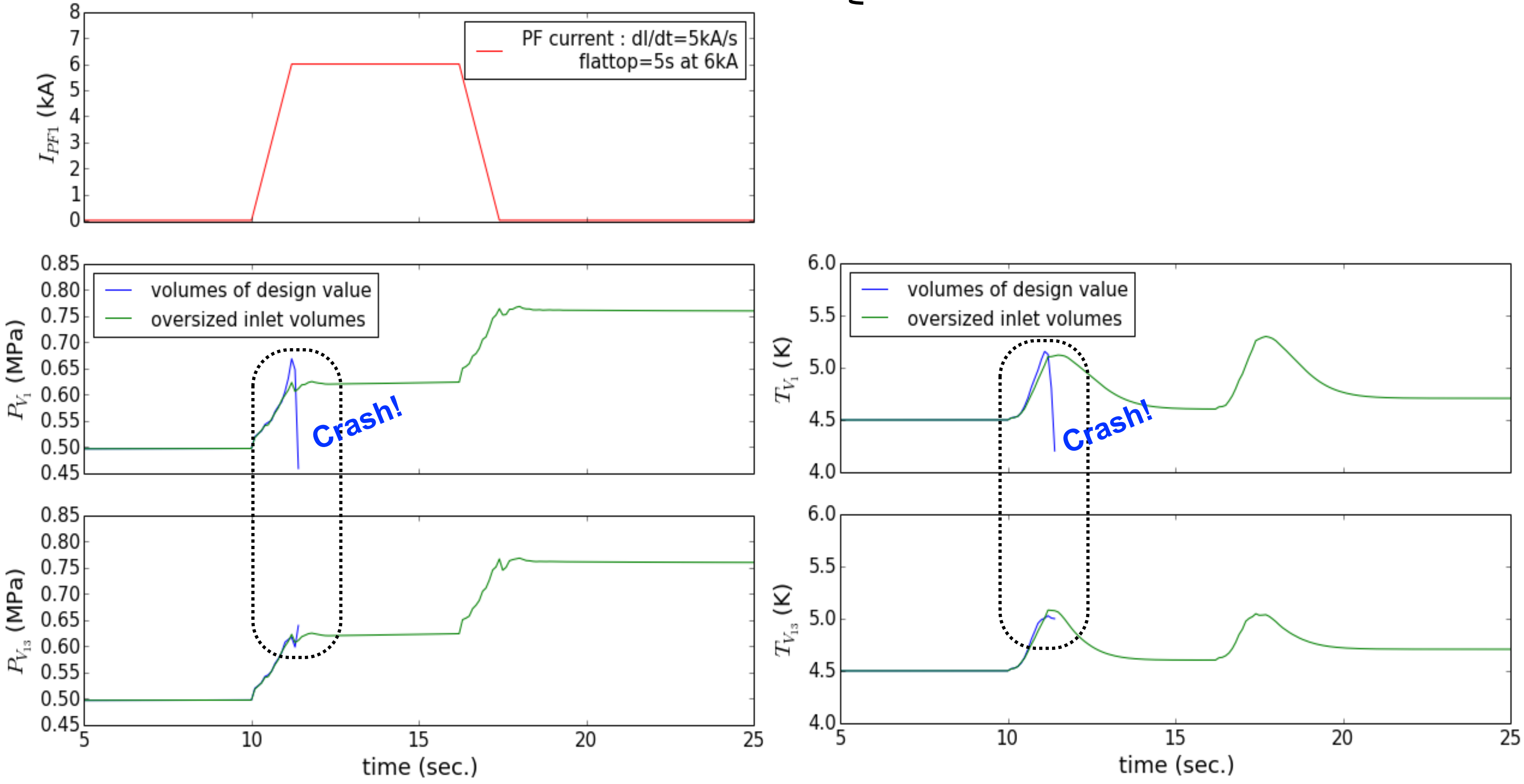
V1-5 & V12-16 : 20 cm^3
V23 & V25 : 200 cm^3



Motivation II (continued)

: Large inlet volumes relieves the trouble.

V1-5 & V12-16 : 20 cm^3 ➡ 40 cm^3 (x2)
V23 & V25 : 200 cm^3 ➡ 400 cm^3 (x2)



Motivation II (continued)

Reasoning

- A stiff change in volume may be originated from the energy flux without careful consideration of momentum transfer at the branches.

- Even a small deviation of boundary velocity can make meaningful changes in the energy flux, in spite the kinetic term itself is negligible.

$$V\frac{\partial P}{\partial t}+\sum_k A_k\rho_k\underbrace{(v_k+\delta v_k)}_{\text{This error will be amplified}}\times\left(c^2+\phi(h_k-h+\tfrac{1}{2}\underbrace{(v_k+\delta v_k)}_{\text{This amount itself is small}}{}^2)\right)=\phi V\dot{q}$$

➔ We are going to count the momentum transfer at the coupled ends to resolve it.

Criticism

- Is the instability solely affected by that reason?
- What about alternative numerical schemes to stabilize the solution as a pragmatic approach?

  ex) non-oscillating scheme for hyperbolic system or higher order of of ODE solver of coupled network

Design principles of the experimental upgrade

Minimal update

- No revision of the basic structure

: Keeping the linearization scheme of FEM based 1-D flow solver
coupled to the 0-D components which are *conceptually FVM*

- New components (one 0-D, one 1-D and one virtual 0-D) into the code with a revision in the part of boundary conditions

Retrofit design

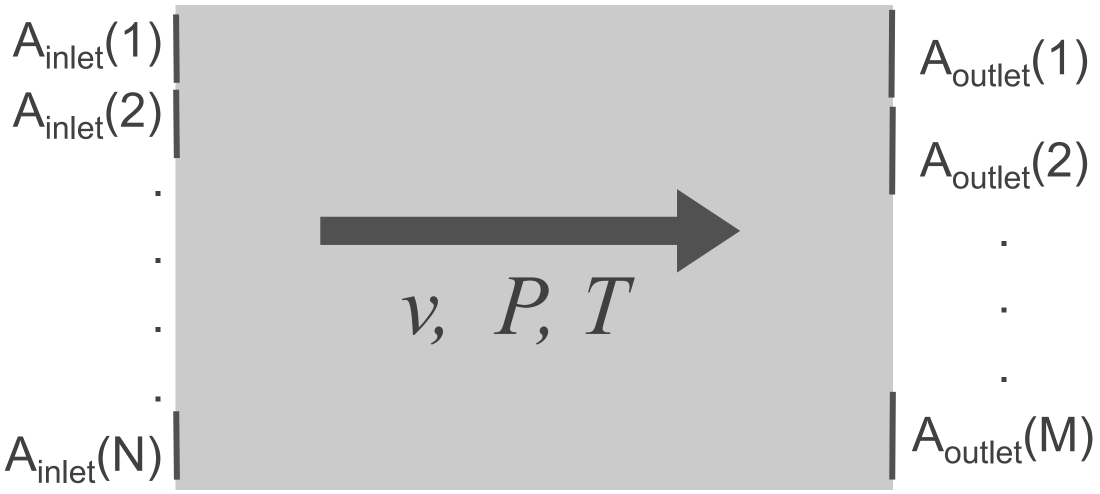
- Compatible to the existing input commands and models
- New 0-D components → corresponding *connection* commands in the 1-D pipe description.

Indirect coupling between the components

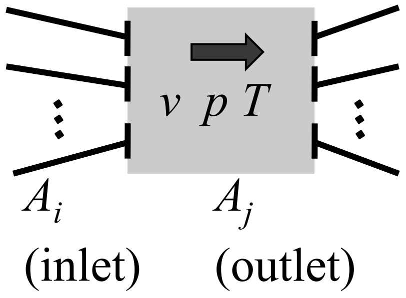
- <u>Fluxes at the surface of the 0-D components = BCs of 1-D pipes</u>

: Natural (or flux) boundary condition derived in terms of the *linearization*
: Upwind scheme to assign the boundary fluxes.

Plenum model & Flux boundary condition



A minimal 0D component of <u>nonzero</u> flow – Plenum



- **3 DOFs** : v (velocity), P (pressure), T (Temperature)
- **Quasi-1D flow** from inlet to outlet
  : multiple inlets and outlets
- **No pressure drop** between the inlets and the outlets
  : uniform pressure → the pressure will be a *BC of the pipes…*
- **Upwind quantity** for the momentum and energy flux

Then,

$$\begin{cases} V\rho \dfrac{\partial v}{\partial t} + \sum_k \dot{m}_k (v_k^* - v) = 0 \\ V \dfrac{\partial P}{\partial t} + \sum_k \dot{m}_k \left(c^2 + \phi (h_k^* - h + \tfrac{1}{2} (v_k^* - v)^2) \right) = \phi V \dot{q} \\ V\rho C_v \dfrac{\partial T}{\partial t} + \sum_k \dot{m}_k \left(\phi C_v T + h_k^* - h + \tfrac{1}{2} (v_k^* - v)^2 \right) = V \dot{q} \end{cases}$$

*** upwind quantities.**

Just like the volume, these equations are conceptually equivalent logic to FVM…

Retrofitting the plenum model into FLOWER

Coupling the DOFs of pipes to plenum → New method of boundary condition

(∵ over-specified boundary makes trouble.)

1. Bind boundary pressure to the plenum. (*essential boundary*)

$$\boxed{P_1 = P_0}$$

2. Apply momentum balance to the velocity (v) boundary. (*natural boundary*)

$$[A\cdot U]_{v_1} = \boxed{\frac{\rho_1 v_1}{\overline{\rho}}(\overline{v} - v_0)} + \frac{1}{\overline{\rho}}\left(\frac{P_2 - P_1}{2}\right)$$

3. Set equivalent heat flux for the temperature (T) boundary. (*natural boundary*)

$$[A\cdot U]_{T_1} = \left(\overline{\rho\phi C_v T} + \tfrac{1}{2}\overline{\rho}\left(\overline{v} - v_0\right)^2\right)\left(\frac{v_2 - v_1}{2}\right) + \overline{\rho v}\left(\overline{C_v} - \overline{C_p} - \tfrac{1}{2}\overline{\beta}\left(\overline{v} - v_0\right)^2\right)\left(\frac{T_2 - T_1}{2}\right)$$

$$+ \overline{v}\left(\overline{\beta T} - 1 + \tfrac{1}{2}\overline{\kappa}\overline{\rho}\left(\overline{v} - v_0\right)^2\right)\left(\frac{P_2 - P_1}{2}\right)\boxed{- \rho_1 v_1 (h_0^* - \overline{h})}$$

$$\begin{cases} \kappa = \dfrac{C_p/C_v - 1}{\phi^2 T \rho C_v} \\ \beta = \dfrac{C_p/C_v - 1}{\phi T} \end{cases}$$

: v_0 is plenum velocity, P_0 is plenum pressure and h_0^* is upwind enthalpy

The matrices of the boundary nodes is to be modified according to the above equations…

Note) Correspondence to the original BC in terms of heat flux

Rearranged T equation at the boundary is equivalent to

$$[A\cdot U]_{T_1} = \overline{\rho\phi C_\mathrm{v} T}\left(\frac{v_2 - v_1}{2}\right) + \overline{v\rho C_\mathrm{v}}\left(\frac{T_2 - T_1}{2}\right) \underbrace{- \rho_1 v_1 (h_0^* - \bar{h})}_{\text{Heat coming from the boundary}} - \overbrace{\tfrac{1}{2}\bar{v}\bar{\rho}(h_2 - h_1)}^{\text{Heat to the next element}}$$

$$\underbrace{-\tfrac{1}{2}\left(v_0 - \bar{v}\right)^2 (\rho_1 v_1 - \bar{\rho}\bar{v})}_{\text{Balance of the kinetic energy}}$$

If $h_0^* = h_1$ and $v_0 = v_1$, $[A\cdot U]_{T_1} = \overline{\rho\phi C_\mathrm{v} T}\left(\frac{v_2 - v_1}{2}\right) + \overline{v\rho C_\mathrm{v}}\left(\frac{T_2 - T_1}{2}\right)$

(neglecting 2nd order of the kinetic energy to be consistent with linearization)

This corresponds to the case of $v_1 < 0$ for the pipe inlet (outgoing flow).
So, for the outgoing flow, free boundary of T can be justified.

Note) Flux boundary for the non-conservative form

$$\frac{\partial u}{\partial t}+a\frac{\partial u}{\partial x}+su-\frac{\partial}{\partial x}g\frac{\partial u}{\partial x}=q \;\Rightarrow\; \int_0^L dx\; w\;\frac{\partial u}{\partial t}+\int_0^L dx\; w\; a\frac{\partial u}{\partial x}+\int_0^L dx\; w\;\frac{\partial}{\partial x}g\frac{\partial u}{\partial x}+\int_0^L dx\; w\; s\; u=\int_0^L dx\; w\; q$$

weak form

Assuming $a(x)=a(\overline{U})$ (linearization)

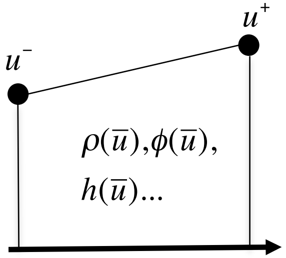
$$\begin{cases}\int_0^L dx\; w_1 a\frac{\partial u}{\partial x}=-a(0)U_1-\int_0^{\Delta x} dx\left(w_1\frac{\partial a}{\partial x}+a\frac{\partial w_1}{\partial x}\right)u=a(\overline{U})U_1-\int_0^{\Delta x} dx\; w_1 a(\overline{U})\frac{\partial w_1}{\partial x}\\ \int_0^L dx\; w_{\mathbf{n}} a\frac{\partial u}{\partial x}=a(L)U_{\mathbf{n}}-\int_{L-\Delta x}^L dx\left(w_{\mathbf{n}}\frac{\partial a}{\partial x}+a\frac{\partial w_{\mathbf{n}}}{\partial x}\right)u=-a(\overline{U})U_{\mathbf{n}}-\int_{L-\Delta x}^L dx\; w_{\mathbf{n}} a(\overline{U})\frac{\partial w_{\mathbf{n}}}{\partial x}\end{cases}$$

natural boundary

revised component of avection (A) matrix

The key point is to express $a(\overline{U})U_1$ & $a(\overline{U})U_{\mathbf{n}}$ *in terms of momentum and energy flux* at the interface (*i.e.* plenum's surface).

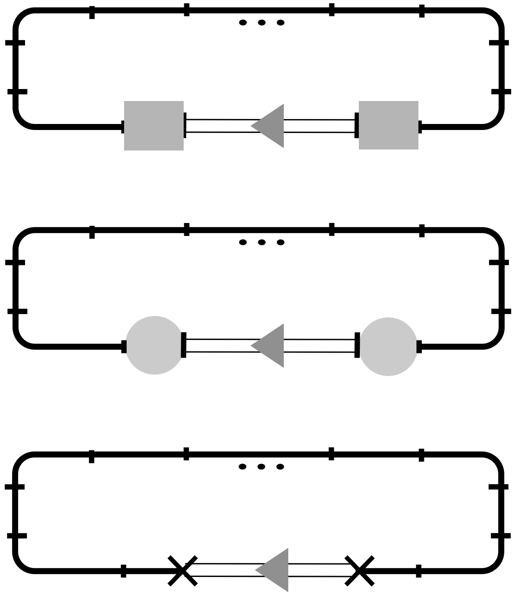
➔ Based on the <u>linear property</u> in our FEM elements,



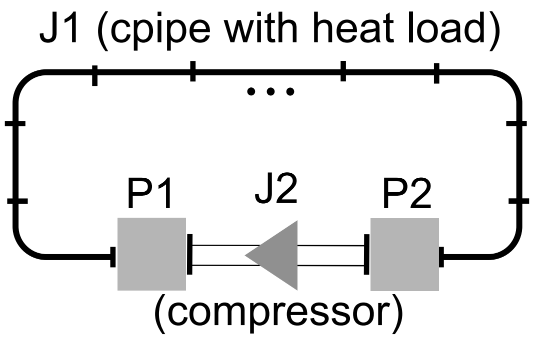
- $\underbrace{\overline{\rho v}v^+ + P^+}_{\overline{a}U_1 \;\; or \;\; \overline{a}U_n} = \Gamma_p^+ - (\rho v)^+\overline{v} + \overline{\rho v}\,\overline{v} = (\rho v)^+(v^+ - \overline{v}) + P^+ + \overline{\rho v}\,\overline{v}$
- $\underbrace{\overline{\rho\phi C_{\mathrm{v}}T}\; v^+ + \overline{v\rho C_{\mathrm{v}}}T^+}_{\overline{a}U_1 \;\; or \;\; \overline{a}U_n} = (\overline{\phi C_{\mathrm{v}}T - h + \tfrac{1}{2}v^2})\Gamma_m^+ - \overline{v}\;\Gamma_p^+ + \Gamma_e^+ + \overline{v\rho C_{\mathrm{v}}T} + \overline{vP} - \tfrac{1}{2}\overline{\rho v}\left(v^+ - \overline{v}\right)^2$

$$= \overline{\phi C_{\mathrm{v}}T}(\rho v)^+ + \overline{\rho v C_{\mathrm{v}}T} + (\rho v)^+(h^+ - \overline{h}) - \overline{v}(P^+ - \overline{P}) + \tfrac{1}{2}\left((\rho v)^+ - \overline{\rho v}\right)\left(v^+ - \overline{v}\right)^2$$

Test runs of the experimental components



Test #1



A FLOWER model
with plena

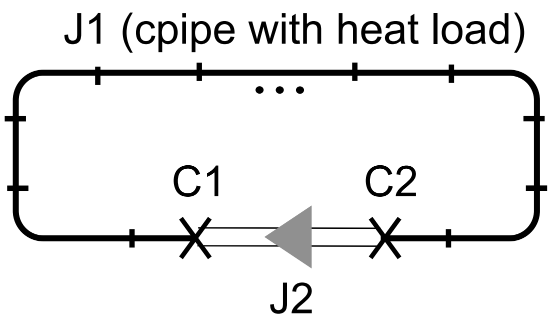
J1 : 10 m (L), ~3 mm (D)
J2 : 1 m (L), 1cm (D)

P1 & P2 : 1 cm^3

Heat load : 1 W/m,
uniformly loaded to J1)

```
 Begin Simulation
  StartTime   0.0
  EndTime     100.0
  TimeStep    5.e-2
  OutputStep  5.e-2
  StorageFile  oldpumpp.store
  LogFile      oldpumpp.log
   title         'Simple heated loop with an old pump'
  Plena          2
   Junctions      2
End

Begin Plenum 1  ; inlet plenum node
   V 1.0e-6  P 5e5   T 4.5
End

Begin Plenum 2  ; outlet plenum node
   V 1.0e-6  P 5e5   T 4.5
End

Begin Junction 1
   type Cpipe
  connection PO1 PI2
   L 10.0   A 3.14e-5  Dh 3.0e-3  N 25
   WP 3.14e-3
   Heating window Q 1.0 tauQ 100.0
End

Begin Junction 2
   type Compressor
   connection PO2 PI1
   L 1.0   A 3.14e-4
   m0 1.0e-3   Dp0 1.00e5  taup 0.2e0
End
```

Test #1-1 :benchmarking



(compressor)

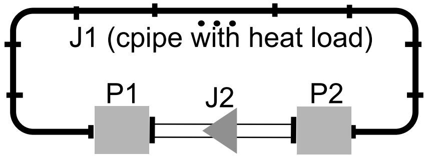
A FLOWER model

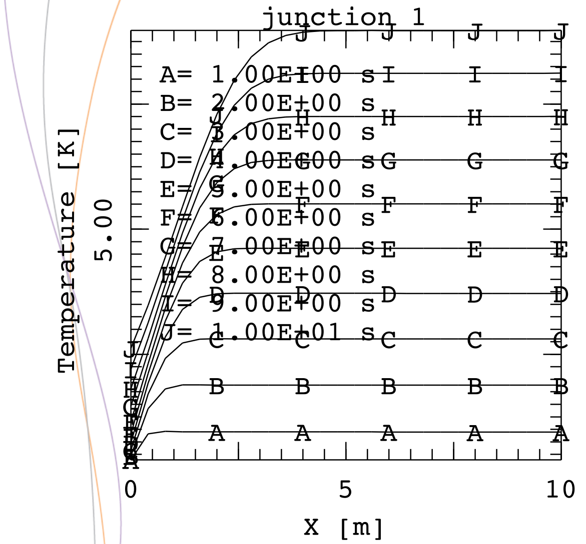
with coupling points

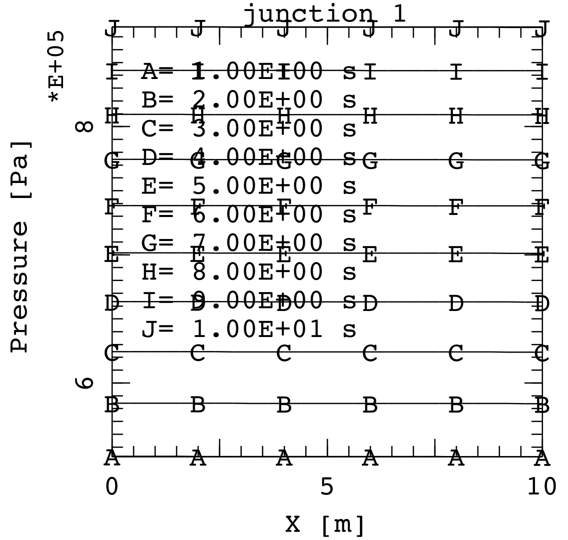
- Set the boundary velocity of Cpipe at the constraint of J2's massflow.
- Heat (enthalpy) flux is assigned to the boundary P and T of Cpipe.
- Enthalpy evolution in J2 (SSpipe) is computed using P and T in the same way of the SSpipe attached to a plenum.

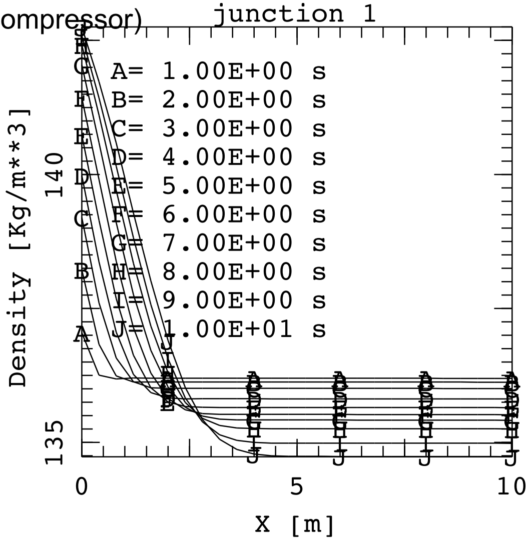
```
 Begin Simulation
  StartTime    0.0
  EndTime      100.0
  TimeStep     5.e-3
  OutputStep   5.e-2
  StorageFile   oldpumpp.store
  LogFile       oldpumpp.log
   title          'Simple heated loop with an old pump'
  Cpoints          2
   Junctions        2
End

Begin Cpoint 1  ; inlet cpoint node
   P 5e5   T 4.5
End

Begin Cpoint 2  ; outlet cpoint node
   P 5e5   T 4.5
End

Begin Junction 1
   type Cpipe
  connection C1 C2
   L 10.0   A 3.14e-5  Dh 3.0e-3  N 200
   WP 3.14e-3
   Heating window Q 1.0 tauQ 100.0
End

Begin Junction 2
   type Compressor
   connection C2 C1
   L 1.0   A 3.14e-4
   m0 1.0e-3   Dp0 1.00e4  taup 0.2e0
End
```

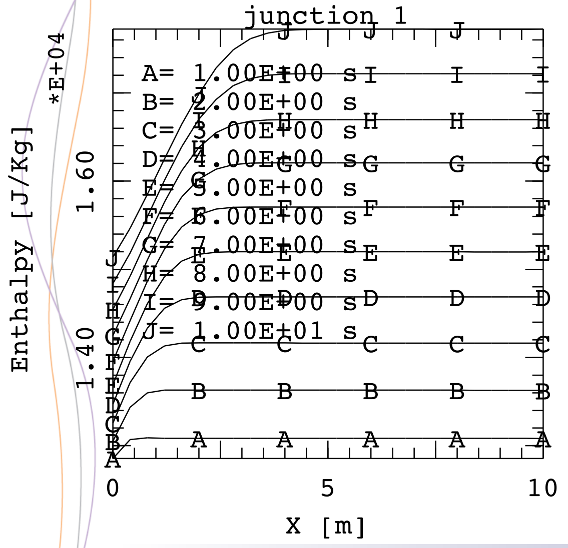
Test #1 : result

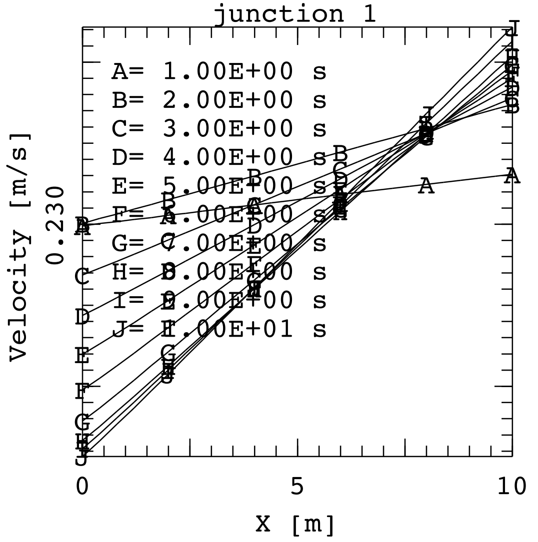


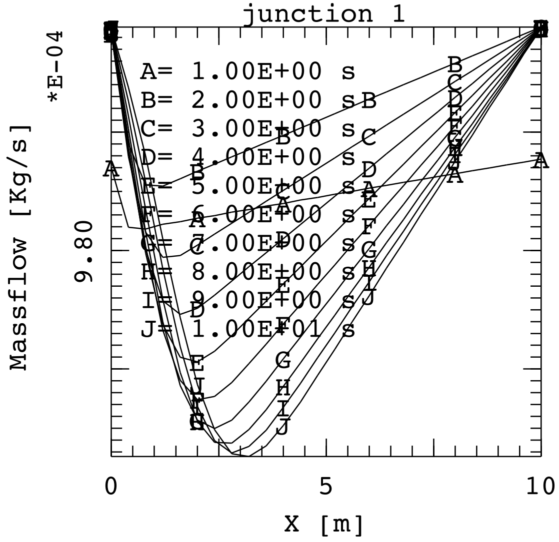




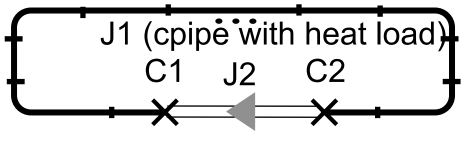


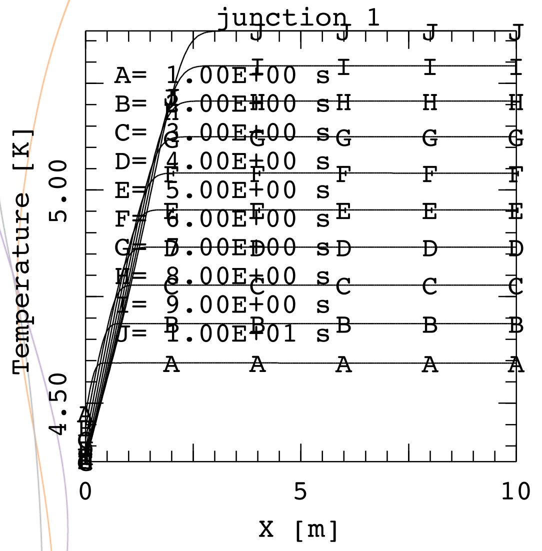


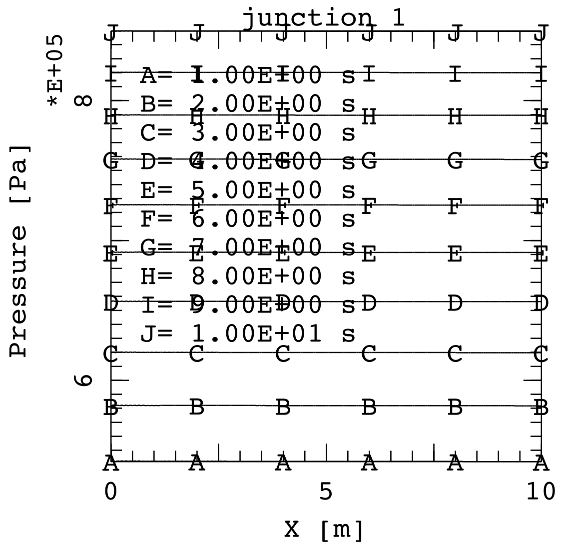


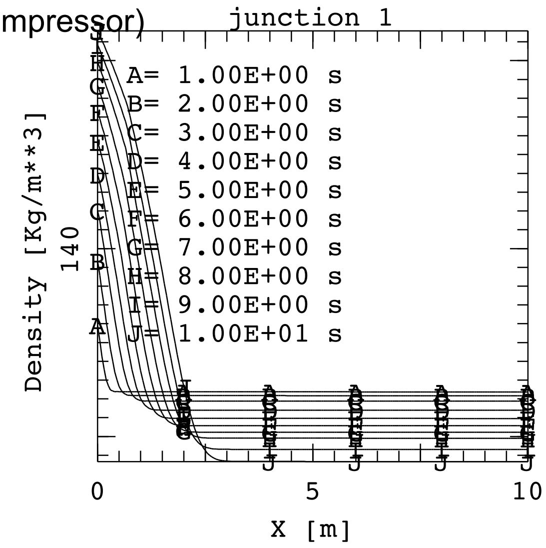


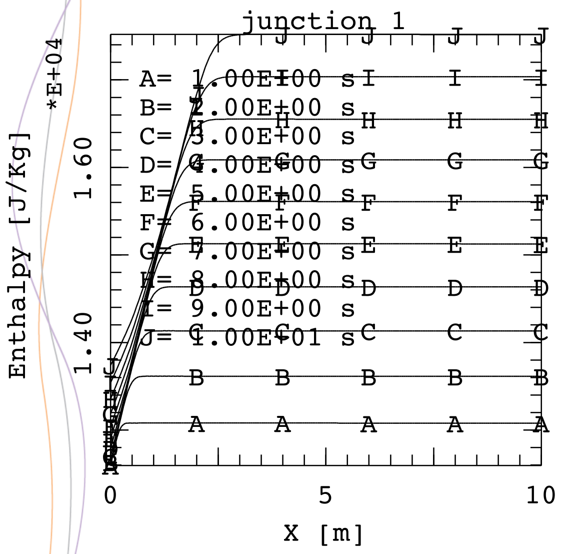
Test #1-1 : result

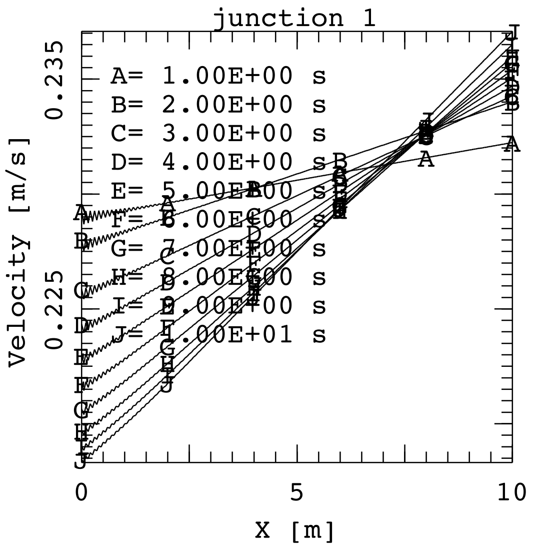


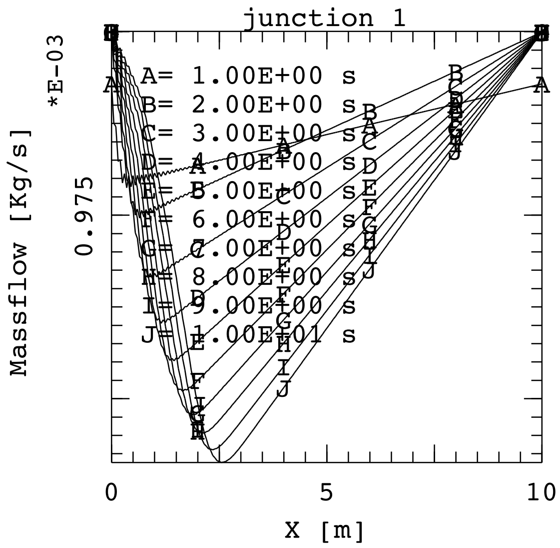




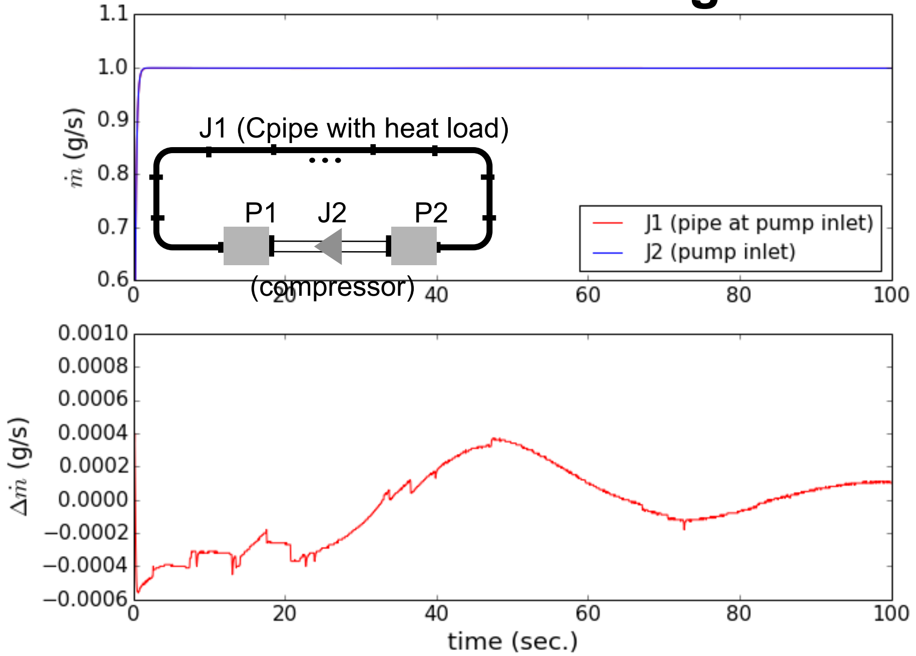


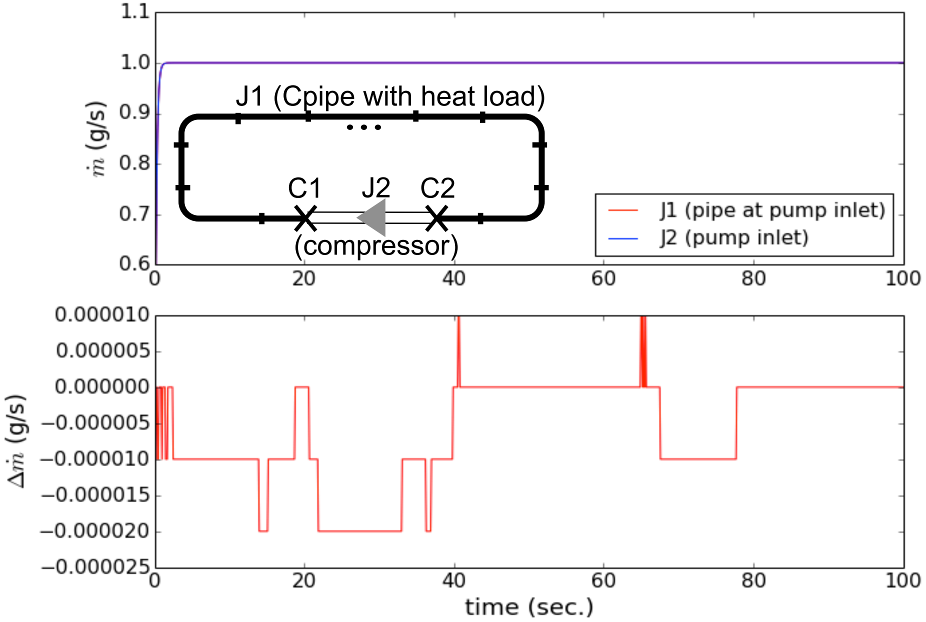


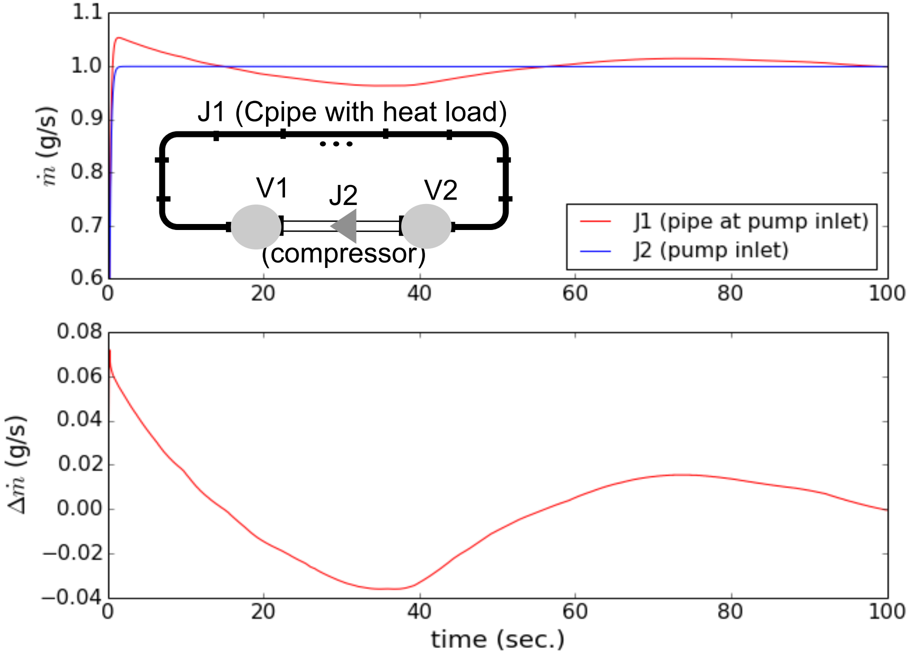




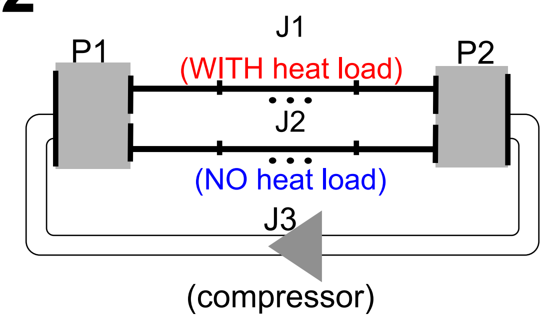
Test #1 & #1-1 : looking into the mass flow







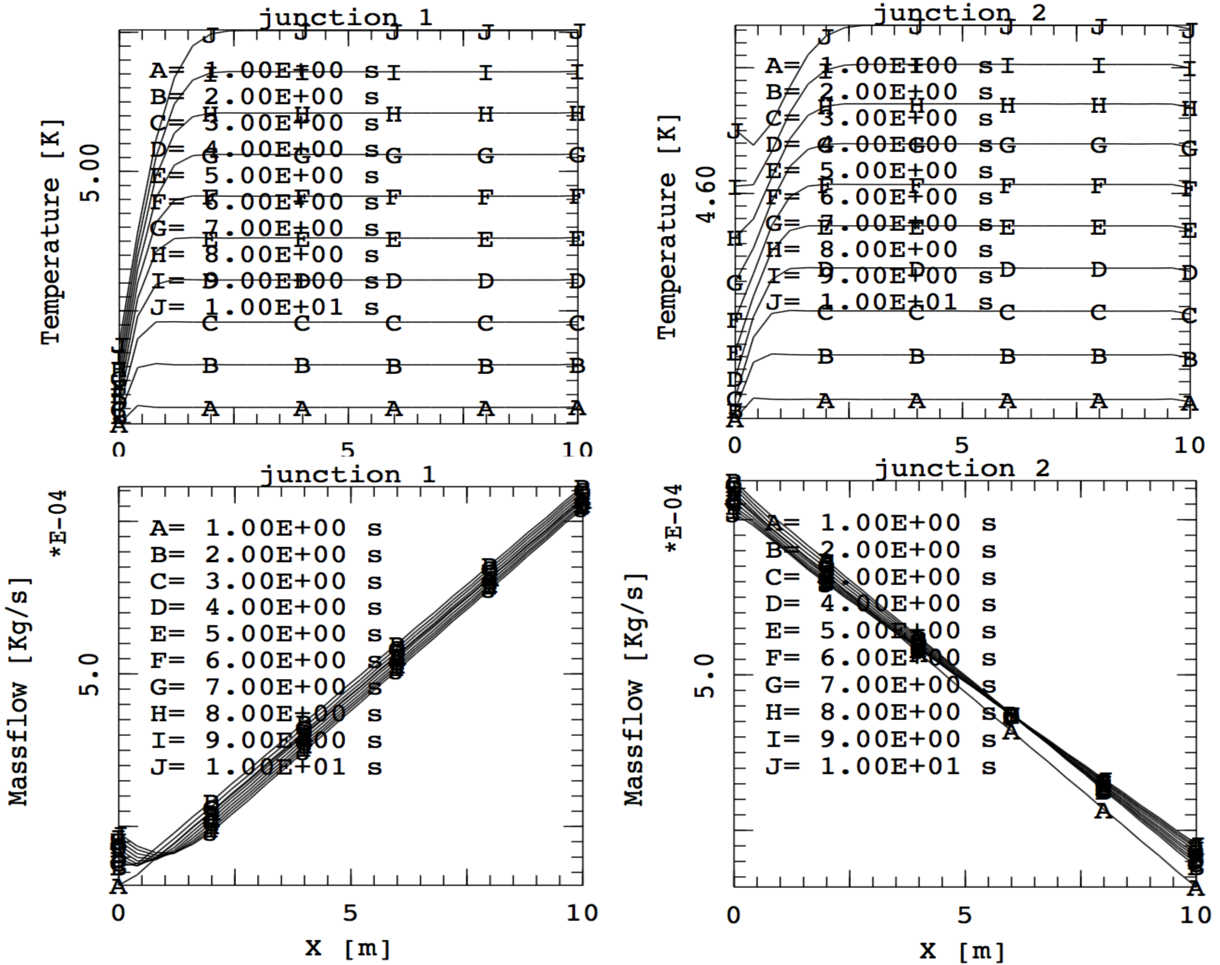
Test #2

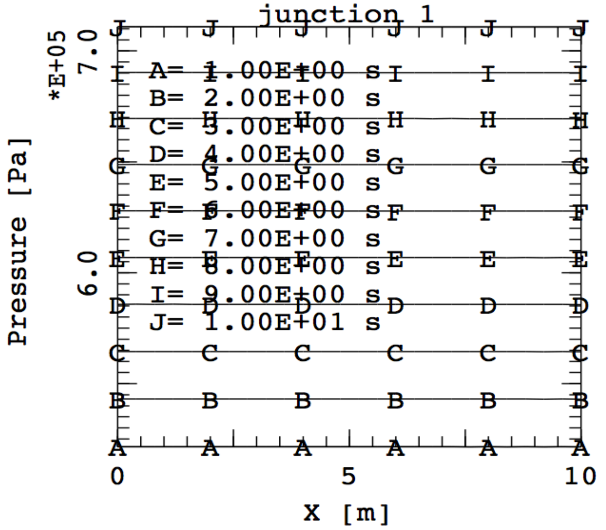


J1, J2 (Cpipes): 10 m (L), ~3 mm (D)
J3 (SSpipe) : 1 m (L), 1cm (D)

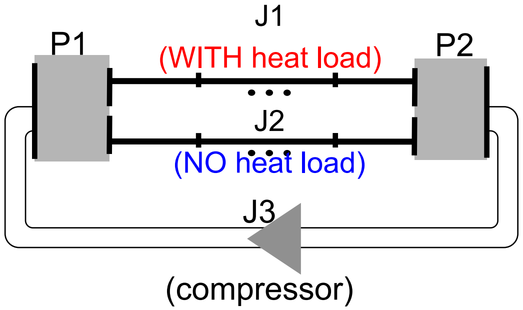
P1 & P2 : 1 cm^3

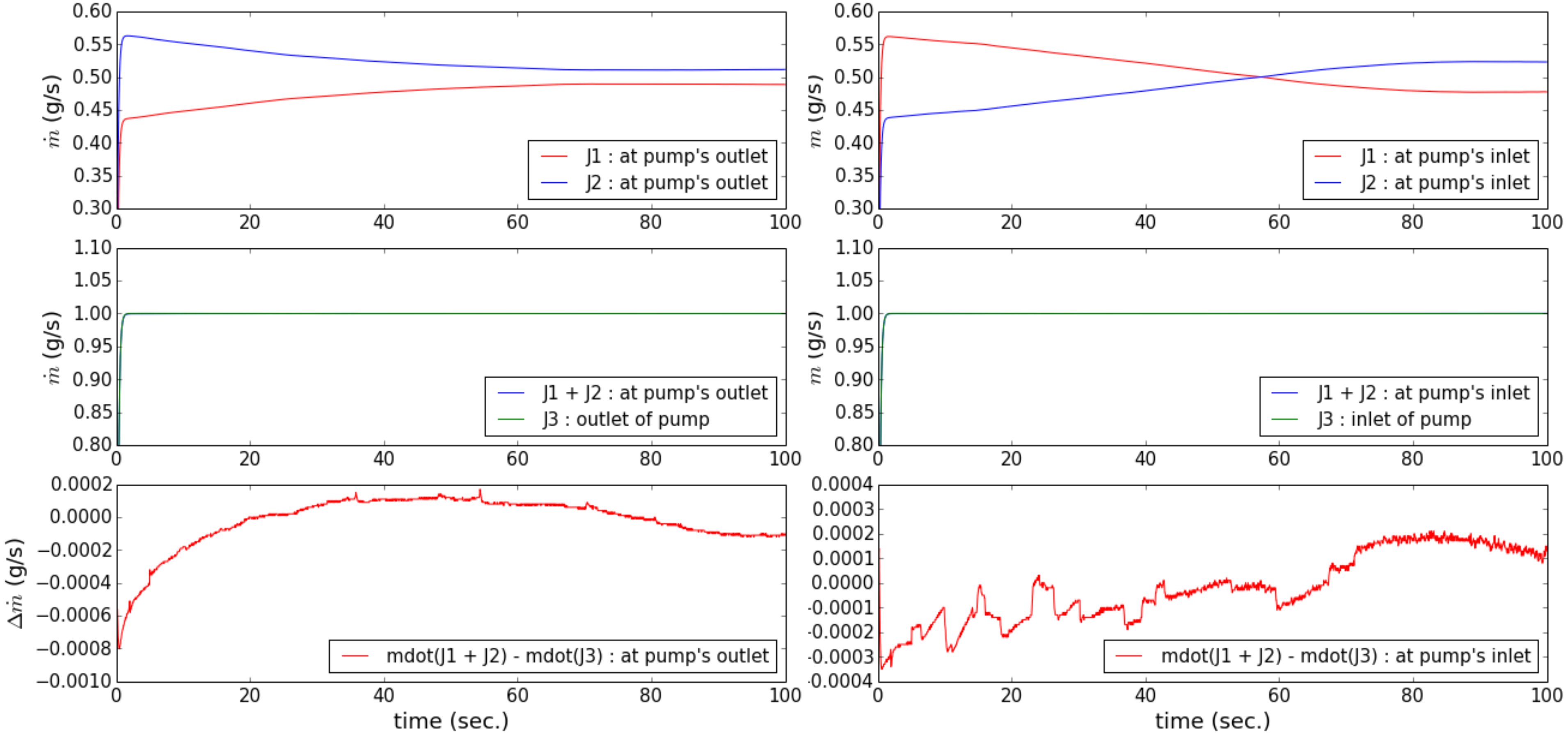
Heat load : 1 W/m,
(uniformly loaded to J1)



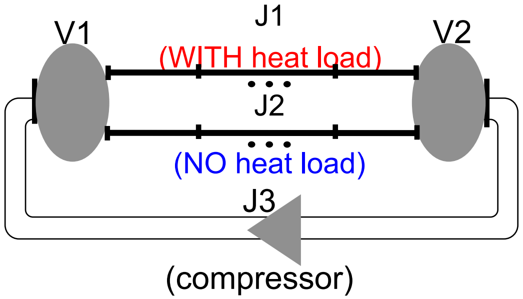


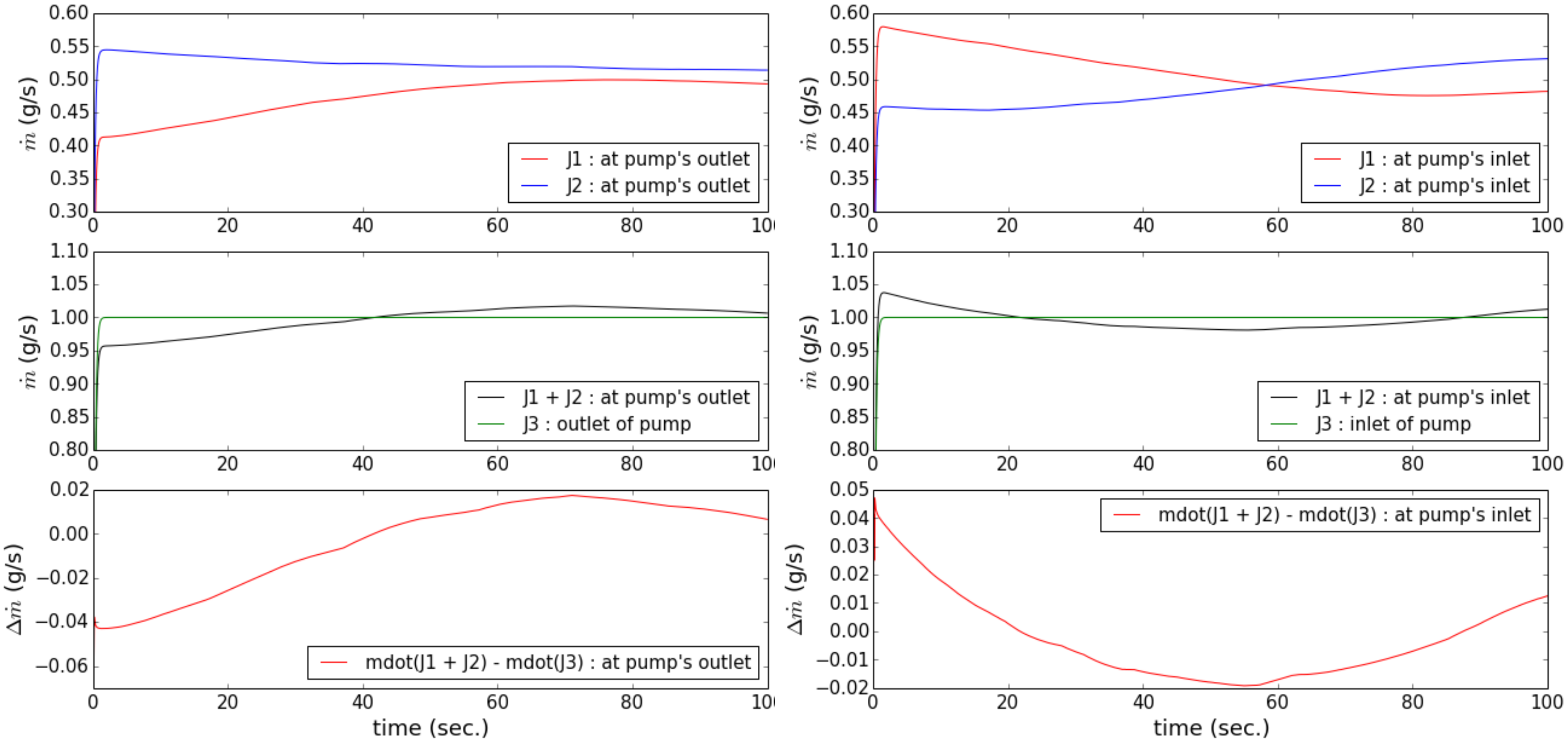
Test #2 : looking into the mass flow



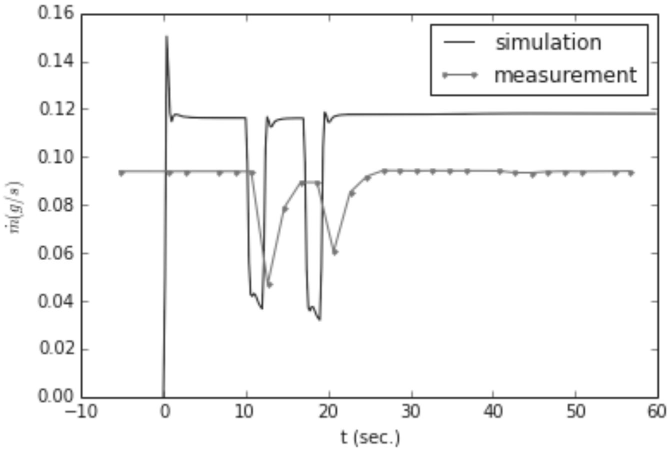


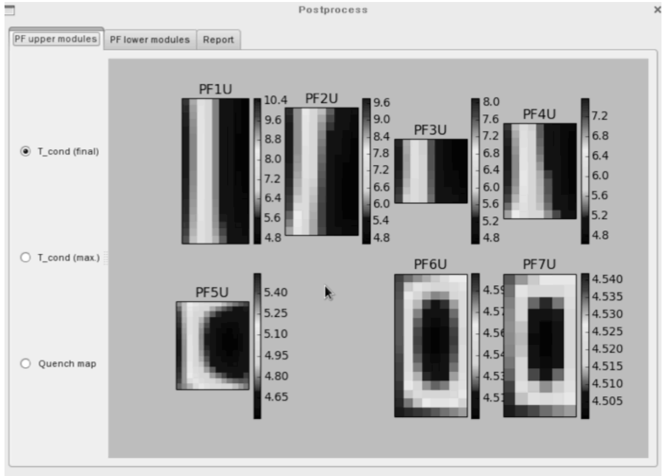
Test #2-1 :comparison with the volumes





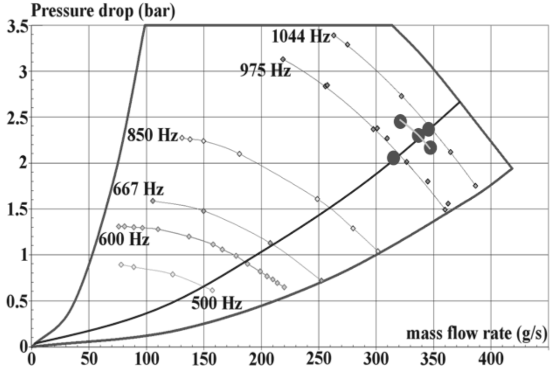
Conclusion and discussion





A long time ago in KSTAR far,.
far away,

In-house codes were developed
also for quench propagation
analysis in 1999~2002
with improved adaptive mesh
(QSAIT and MFEM1D)
and operation analysis



✓ **Gain**

- Implementing an idea to reflect the momentum and heat transfer on the flow at branching nodes
- Technical progress to build more realistic components, and in particular, to tackle the stability issues.

✓ **To do**

- Full assessment of self-consistence (ex> the conservation laws) for the new scheme of the boundary and custom components.
- Verifying the impact on the performance of SUPERMAGNET model; we have to work for THEA code in the same way.

So what?

- A study for an idea to improve the cryo-loop solver

- For full-scale KSTAR PF magnet simulator, some technical issues are undertaken.

  : *Adding up or modifying the routines for practical properties of real-world components*

  : *Getting more stable solver of the coupled models*

- Based on the work, more pragmatic study can be emerged to develop an alternative routines of better performance and stability.

- To do that, verification and benchmarking for our results should be go on as a prerequisite.