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Mixing Flows in Dynamic Fluid Transport Simulations

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- introduction
- modeling of mixing flows
- temperature modeling
- numerical experiments

Introduction

Multi-phYsics

MYNTS

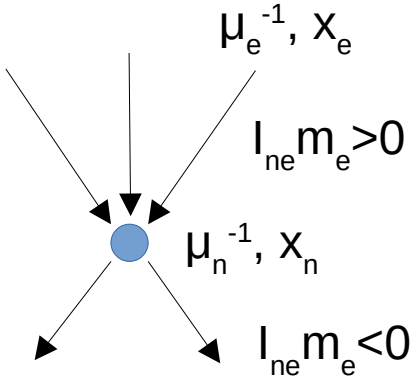
NeTwork Simulator

- this development is a part of our software

- in MYNTS, fluid transport modeling is based on
- conservation of mass, molar and energy flows
- Darcy-Weisbach pipeline pressure drop formula, with empirical friction term by Nikuradse and Hofer
- equation of state computation by simplified analytical Papay model or more complex ISO-norm models AGA8-DC92 and GERG2008
- customer-specific models of compressors and pumps

- this work describes in details the modeling of mixing flows and temperature in MYNTS

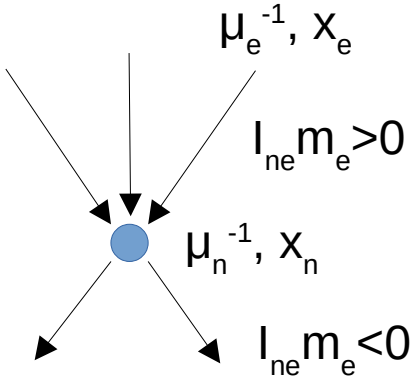
Modeling of mixing flows



- fluid transport network is a directed graph
- described by an incidence matrix I_{ne}
- each edge e has nonzero entries for the nodes n that this edge connects
- -1 for the node that edge comes from,
- $+1$ for the node that edge enters

- variables: V_n is the volume assigned to the node
- ρ_n is the mass density; m_e is the mass flow in an edge
- $\mu_{n/e}$ is the molar mass
- $x_{n/e}$ are the mole fractions of fluid components
- t is time (dynamic simulation)

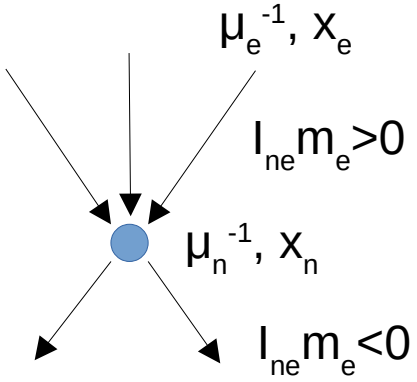
Modeling of mixing flows



- mixing fluid flows are described by following equations
- Kirchhoff eqn: mass conservation
- mixing eqs: molar count conservation

$$V_n \partial \rho_n / \partial t = \sum_e I_{ne} m_e,$$
$$V_n \partial (\rho_n \mu_n^{-1}) / \partial t = \sum_e I_{ne} m_e \mu_e^{-1},$$
$$V_n \partial (\rho_n \mu_n^{-1} x_n) / \partial t = \sum_e I_{ne} m_e \mu_e^{-1} x_e,$$

Modeling of mixing flows



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change of mass in the node

$$V_n \partial \rho_n / \partial t = \sum_e I_{ne} m_e,$$

mass flow in the node

$$V_n \partial (\rho_n \mu_n^{-1}) / \partial t = \sum_e I_{ne} m_e \mu_e^{-1},$$

$$V_n \partial (\rho_n \mu_n^{-1} x_n) / \partial t = \sum_e I_{ne} m_e \mu_e^{-1} x_e,$$

Modeling of mixing flows

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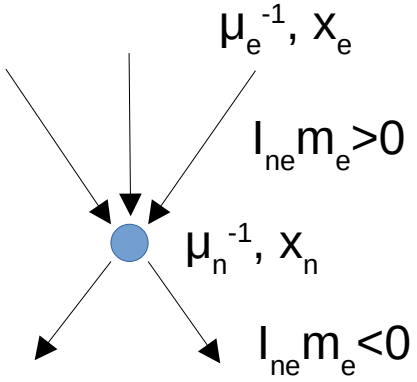

change of mole count in the node

$$V_n \partial \rho_n / \partial t = \sum_e I_{ne} m_e,$$

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molar flow in the node

Modeling of mixing flows

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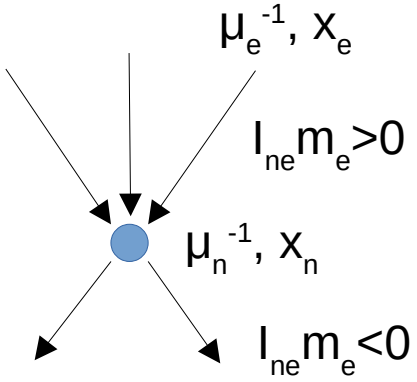

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change of component mole count in the node

component molar flow in the node

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Modeling of mixing flows

- more convenient form, resolved with respect to derivatives

$$V_n \rho_n \partial \mu_n^{-1} / \partial t = \sum_e{}' I_{ne} m_e (\mu_e^{-1} - \mu_n^{-1}),$$
$$V_n \rho_n \mu_n^{-1} \partial x_n / \partial t = \sum_e{}' I_{ne} m_e \mu_e^{-1} (x_e - x_n),$$
$$\sum_e{}' = \sum_{e, I_{ne} m_e > 0},$$

- boundary conditions in entry nodes: $\mu = \mu_{set}$, $x = x_{set}$
- startup: zero massflows, all eqs initially satisfied

Temperature modeling

- variables: U is the molar internal energy
- H = U + P μ/ρ is the molar enthalpy, P is the pressure

- equations: energy conservation for open systems

change of internal energy in the node

$$V_n \partial(\rho_n \mu_n^{-1} U_n)/\partial t = \sum_e I_{ne} m_e \mu_e^{-1} H_e,$$

flow of enthalpy in the node

includes work of pressure force at the boundary

Temperature modeling

- more convenient form

$$V_n \rho_n \mu_n^{-1} \partial H_n / \partial t - V_n \partial P_n / \partial t = \\ = \sum\nolimits_e' I_{ne} m_e \mu_e^{-1} (H_e - H_n),$$

- boundary conditions in entry nodes: $H = H_{set}$, or $T = T_{set}$
- gravitational and kinetic terms: $H \rightarrow H + \mu g h + \mu v^2 / 2$, where g is the acceleration of free fall, h is the height, and v is the speed of the fluid
- HT -constraint:

$$H = H_{mod}(P, T, x), \quad \text{(exact)}$$

$$H = H_{mod}(P, T_{prev}, x) + c_p (T - T_{prev}), \quad \text{(linearized)}$$

- H_{mod} is the thermodynamic model for enthalpy,
  $c_p = \partial H_{mod} / \partial T$ is the molar heat capacity

Temperature modeling

- ISO norm GERG2008 used as thermodynamic model
- linearized eqn makes mixing subsystem linear at each iteration step

- other equations

- default element equation (transport of enthalpy)
- applicable to valves, regulators, resistors and shortcuts

$$H_e = m_e > 0 ? H_{n1} : H_{n2}$$

Temperature modeling

- pipe equation:

$$(m_e > 0?(H_{n1} - H_e)\mu_{n1}^{-1} : (H_{n2} - H_e)\mu_{n2}^{-1})|m_e| = \\ = \pi D L c_{ht}(T_e - T_{soil}),$$

- describes heat exchange with soil: T_{soil} is soil temperature, D is pipe diameter, L is pipe length, c_{ht} is heat transfer coefficient

- compressor equation:

$$m_e > 0?(T_e - T_{n1}((|P_{n2}/P_{n1}|^{(\kappa-1)/\kappa} - 1)/\eta + \\ +1)z_{n1}/z_e) : (H_e - H_{n2}) = 0,$$

- describes isentropic compression: κ is isentropic exponent, η is isentropic efficiency, z is compressibility factor

Temperature modeling

- coolers and heaters:

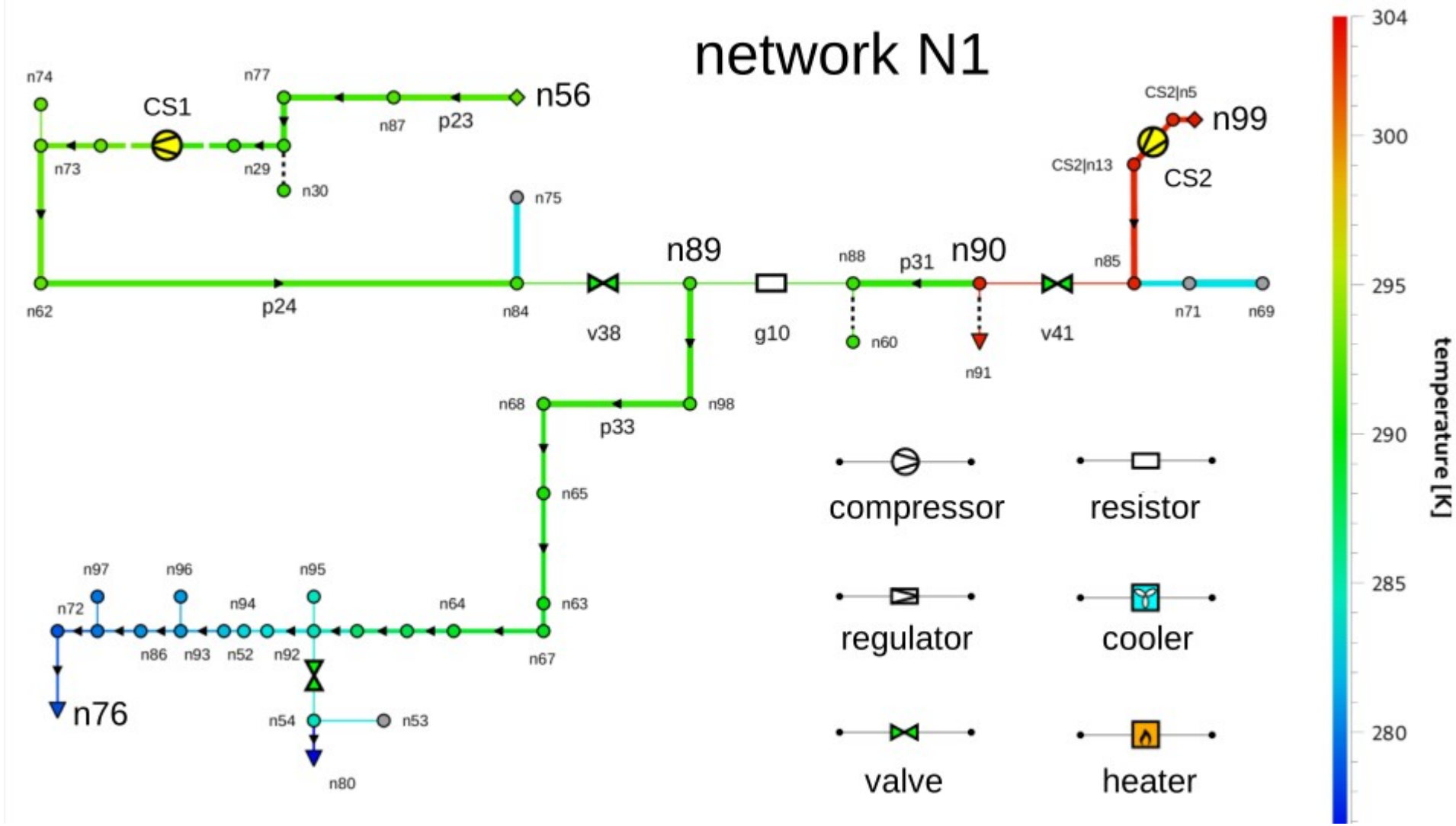
$$m_e > 0?(A_{set} > 0?(T_e - T_{set}) : (H_e - H_{n1})) : (H_e - H_{n2}) = 0,$$

- is a linearization of clamp formulas: $T_e = \min(T_{n1}, T_{set})$ for coolers and $T_e = \max(T_{n1}, T_{set})$ for heaters

Algorithm (active set):
cooler: if(Aset==1&&He>Hn1) then Aset=0; if(Aset==0&&Te>Tset) then Aset=1
heater: if(Aset==1&&He<Hn1) then Aset=0; if(Aset==0&&Te<Tset) then Aset=1

Numerical experiments

- test network
- 100 nodes
- 111 edges
- 2 entries
- 3 exits
- 4 compressors in 2 stations
- filled with nat.gas



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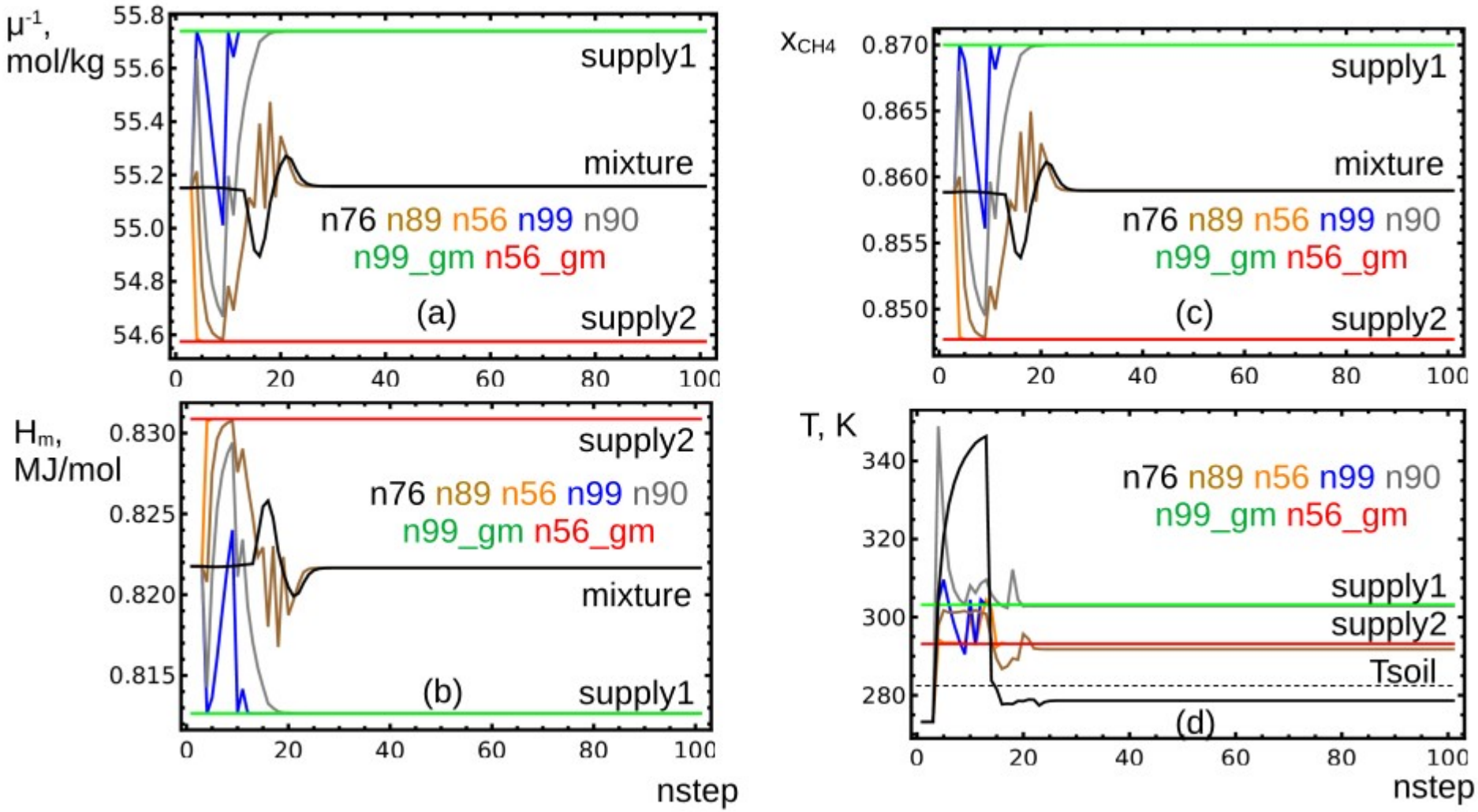
Numerical experiments

- evolution of
- (a) inverse molar mass
- (b) combustion heat value
- (c) methane fraction
- (d) absolute temperature



after startup oscillations, solution goes to stationarity

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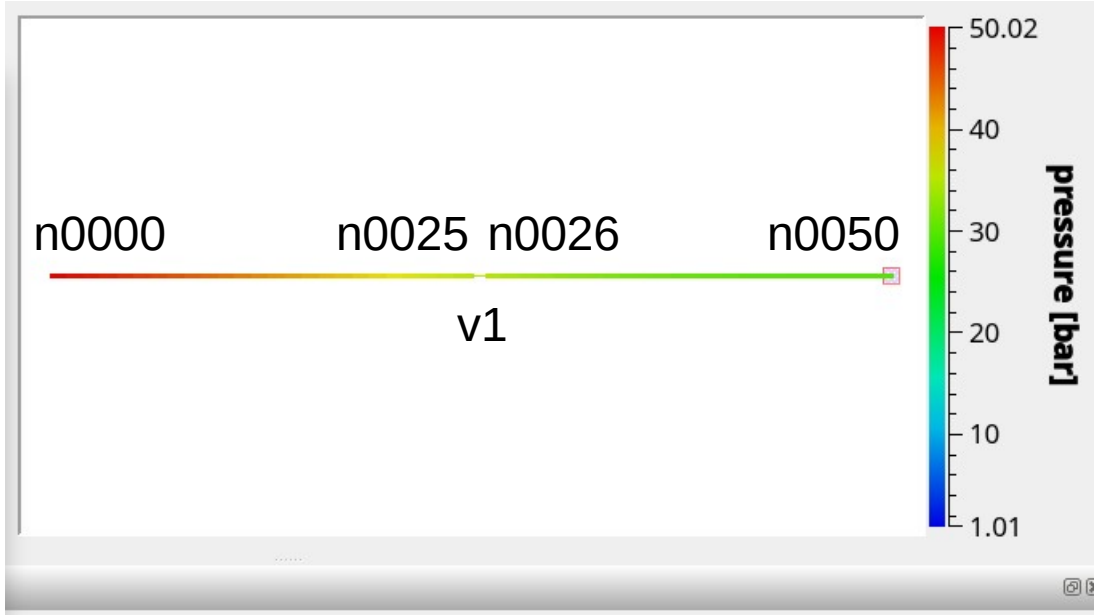
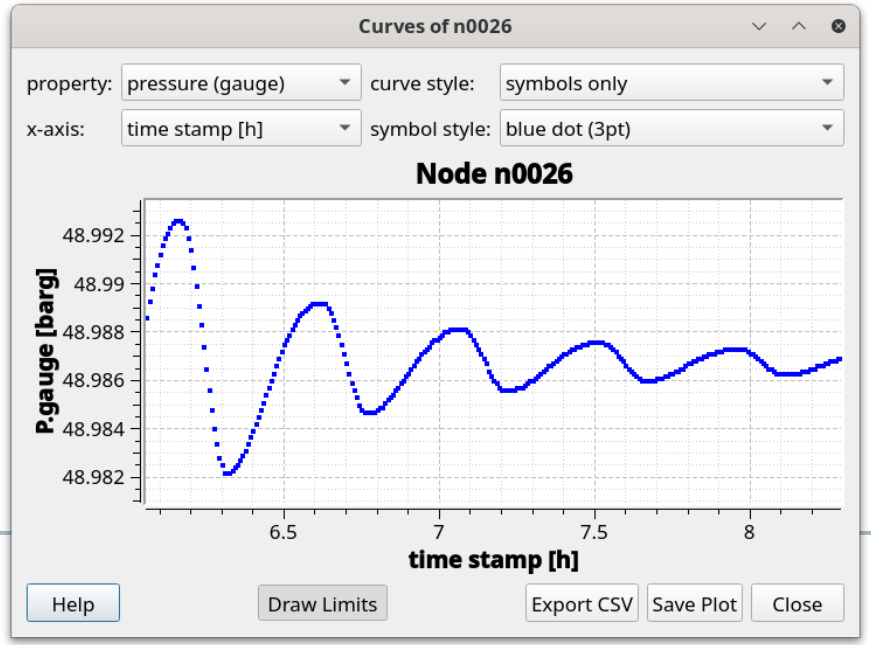
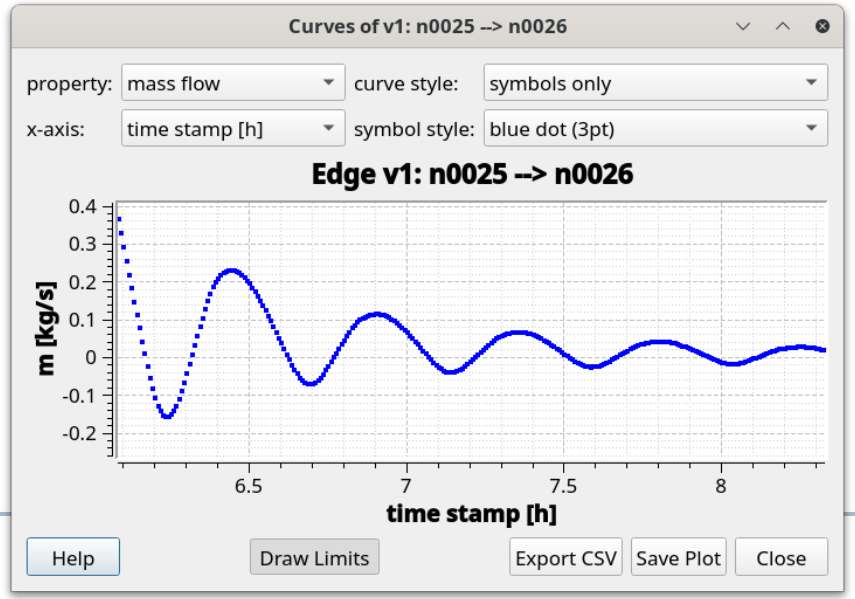
Numerical experiments

- hydrogen and carbon dioxide pipelines
- L = 150km D = 0.5m nsubdiv = 50
- one valve inbetween
- used for testing of the temperature modeling and simulation of shockwaves







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Conclusion

- this work presents a new numerically efficient implementation of flow mixing algorithms in dynamic simulation of pipeline fluid transport
- mixed characteristics include molar mass, heat value, chemical composition and the temperature of the transported fluids
- in the absence of chemical reactions, the modeling is based on the universal conservation laws for molar flows and total energy
- the modeling formulates a sequence of linear systems, solved by a sparse linear solver, typically in one iteration per integration step
- the functionality and stability of the developed simulation methods have been tested on a number of realistic network scenarios

Thank you for your attention