On the Modeling of Aircraft Fuel Systems using the ThermofluidStream Library

Open-source contributions and practical experience

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Aircraft Fuel Systems

SAAB

Purpose:
- Provide fuel to engine
- Pressurize tanks
- Control center of gravity
- Fuel as heat sink

Components:
- Fuel tanks
- Pumps
- Venturi Pumps
- Valves
- Heat exchangers
- Sensors

Challenges:
- Varying acceleration vector
- Both fuel and air

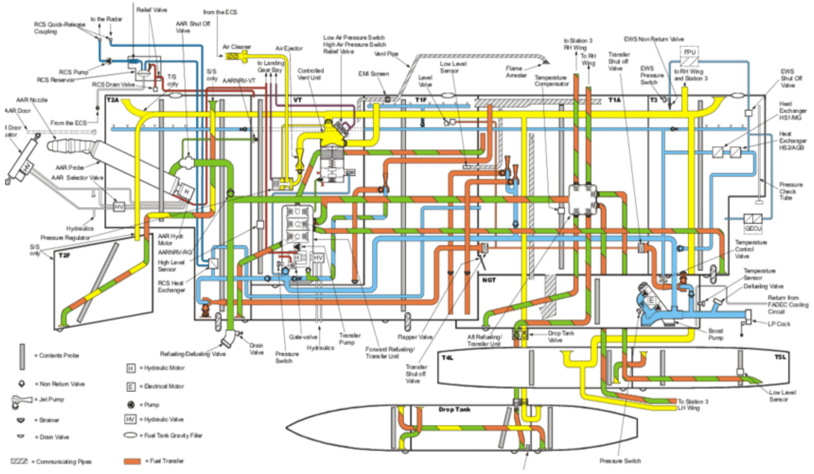


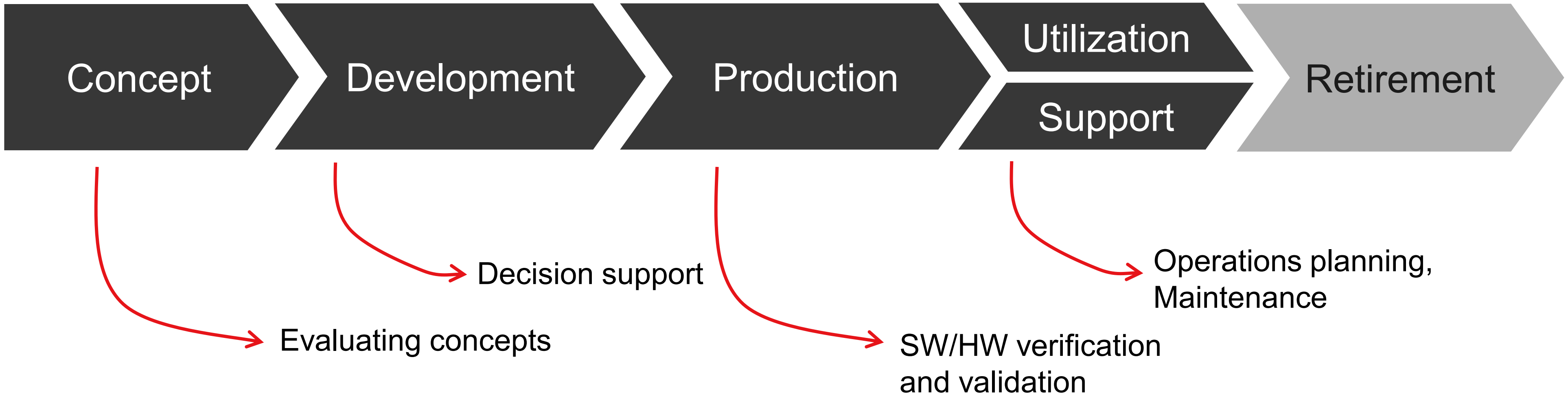
Diagram of Gripen C/D Fuel System

Photo: Linus Svensson @Saab

Use-cases for subsystem simulation

Several use-cases throughout lifecycle

Generic life cycle (ISO/IEC/IEEE 15288:2015)



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ThermofluidStream

- Developed and maintained by DLR
- Open source (https://github.com/DLR-SR/ThermofluidStream)
- Linear Implicit Equilibrium Dynamics (LIED)

Tool compatibility

- Dymola: The library has been developed using Dymola and is based on Modelica 3.2.3. Pedantic checking has been applied to all components in order to improve cross-tool compatibility.
- Open Modelica: To a large extent, the library is compatible to Open Modelica. Details in Issue 10:
- Modelon Impact: The library is reported to be fully compatible to Modelon Impact. Details in Issue 19.

Inertial pressure

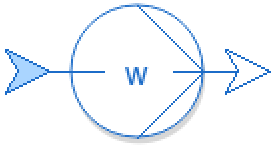
```
connector Inlet
  SI.Pressure r;
  flow SI.MassFlowRate m_flow;

  input Medium.ThermodynamicState
    state;
end Inlet;
```

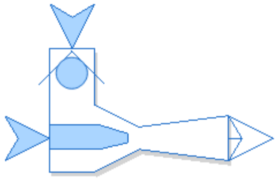
- Temperature
- Steady-state pressure
- Mass fractions

Zimmer, D., Meißner, M., & Weber, N. (2022). The DLR ThermoFluid Stream Library. *Electronics*, *11*(22), 3790.

Pumps, Venturi Pumps

- CentrifugalPump
  - Polynomial fit against existing pump curve
  - Low flow case
- Venturi Pump/Ejector
  - DynamicPressure components
  - Relatively easy to calibrate to measurements
  - Difficult corner cases (e.g. reverse flow)





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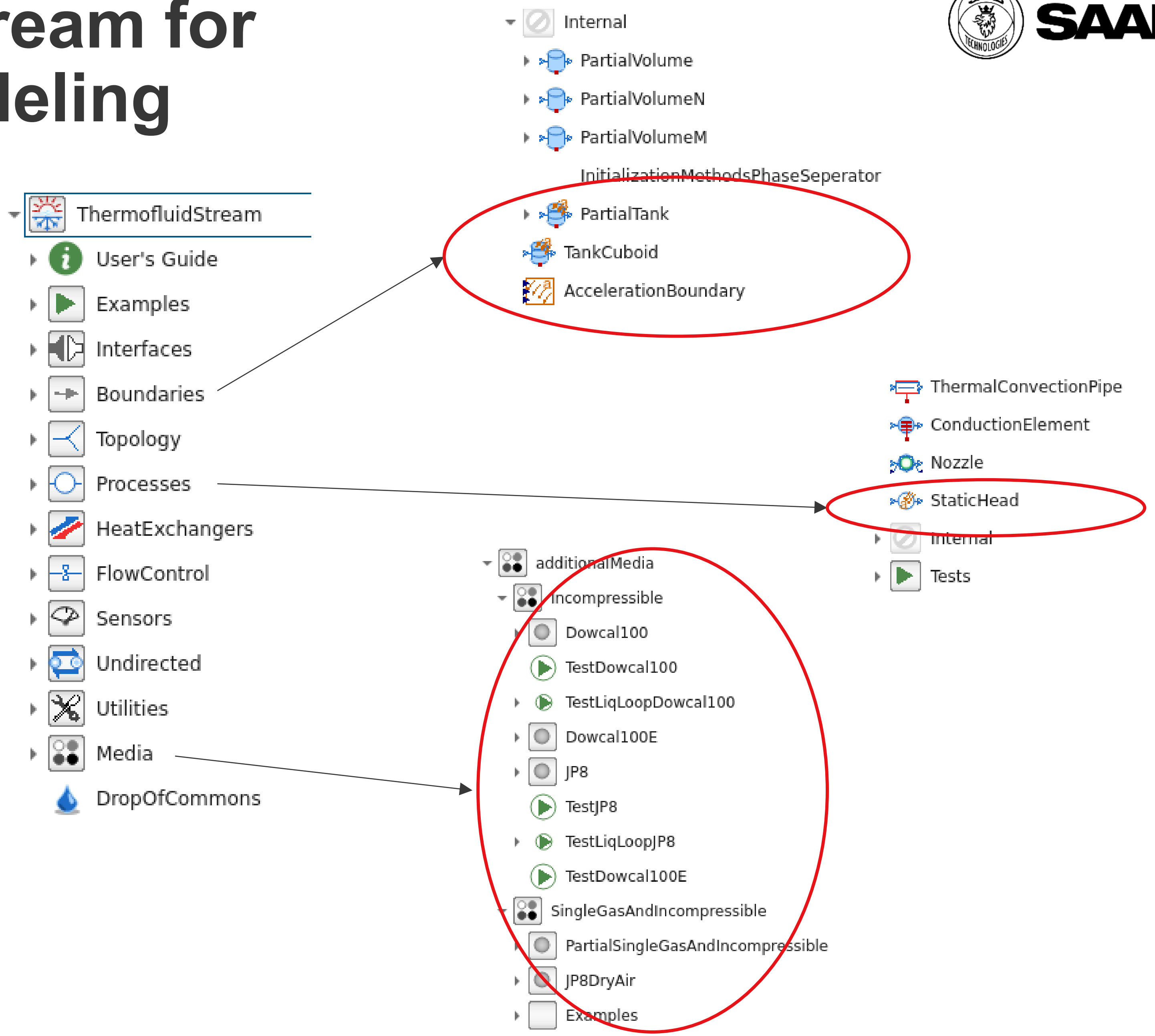
Using ThermofluidStream for A/C Fuel System modeling

Missing functionality:

- Air/fuel mixture media model
- Static head model
- Tank models



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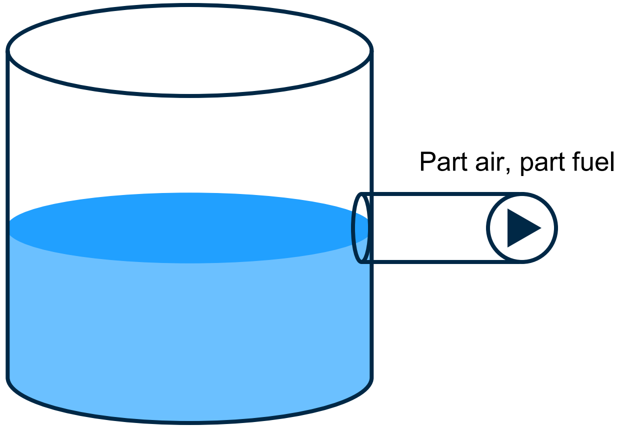
Using ThermofluidStream for A/C Fuel System modeling

Missing functionality:

- Air/fuel mixture media model

Dry air + JP8

- Most properties can be calculated by linear interpolation
- Media model for jet fuel (JP8)



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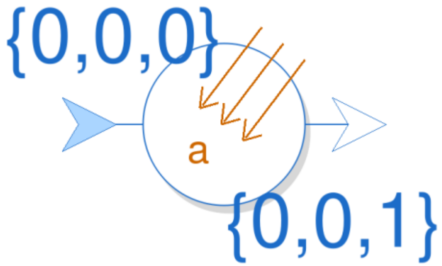
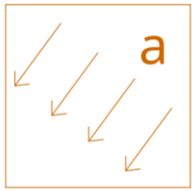
Using ThermofluidStream for A/C Fuel System modeling

Missing functionality:

- Air/fuel mixture media model ✅
- Static head model

- Start, end position specified by parameters
- Acceleration vector specified by global inner/outer class





Using ThermofluidStream for Aircraft Fuel System Modeling

Missing functionality:

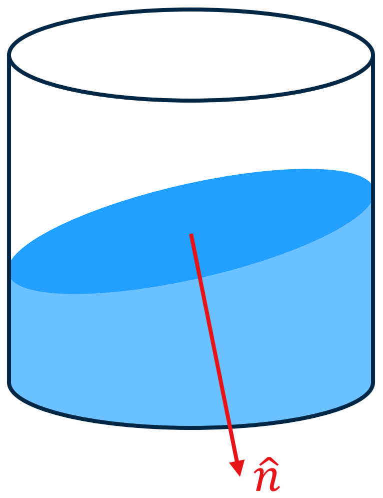
- Air/fuel mixture media model ✅
- Static head model ✅
- Tank models

Assumptions:

- Fuel surface is flat (i.e no slosh, waves) and orthogonal to acceleration vector
- Air pressure is uniform throughout tank (i.e. no gas trapped in concavities)

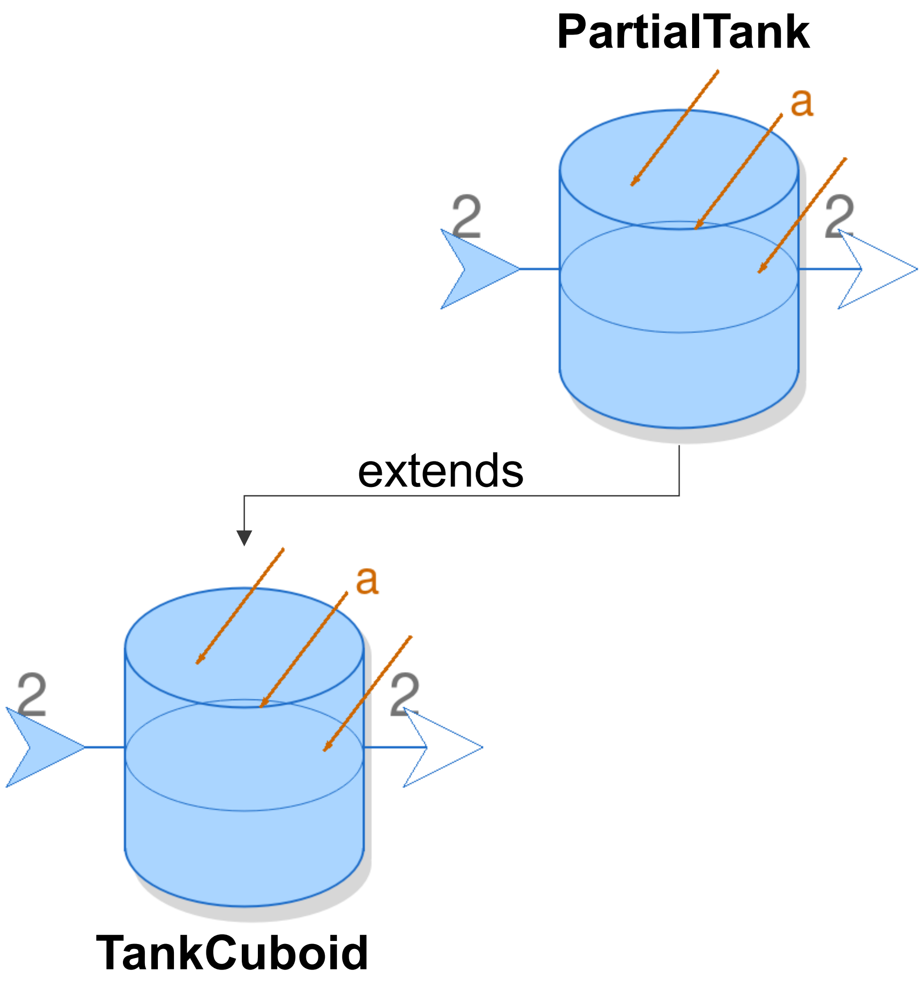
Implementation:

- Arbitrary number of inlets, outlets.
- Outlets carry fuel when below surface, air when above
- Optional thermal port



Tank Models – Partial base class

- PartialTank, PartialTankUndirected
- Enable arbitrary tank geometry
- Handles liquid – air transition
- Nearly full and nearly empty cases
- Positions of connectors within tank



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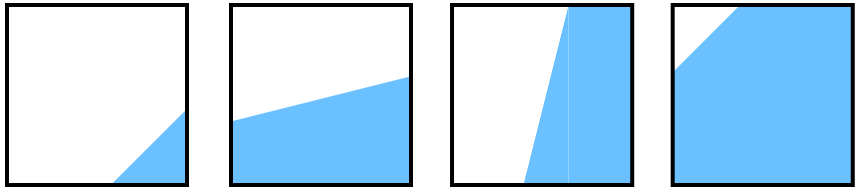
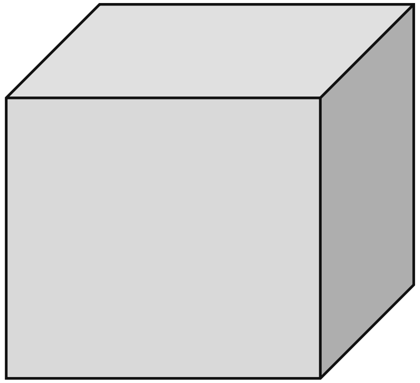
TankCuboid

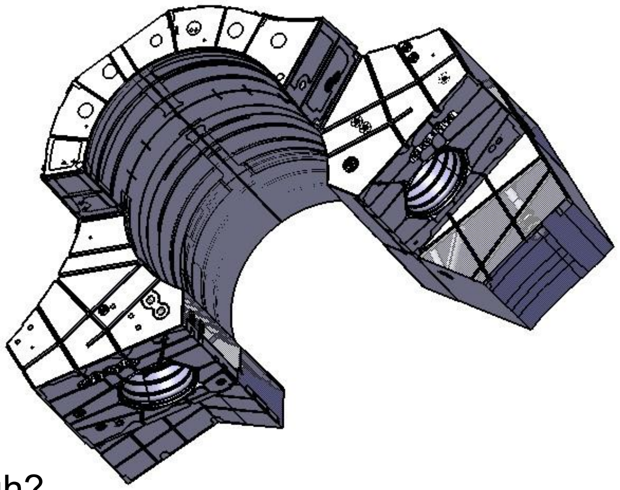
- Analytic solution for cuboid tanks
- Acceleration in xz-plane
- This simplification has worked well, even for non-cuboid shaped tanks
- Acceleration in y axis rarely strong compared to x,z

Photo: Linus Svensson @Saab

Possible cases, acceleration downwards rightwards







Similar enough?

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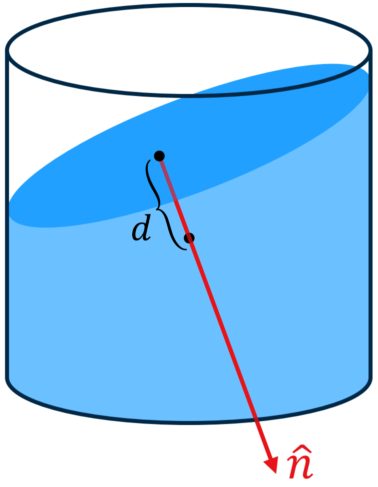
Current focus

Robustness, real geometry

Tanks with arbitrary geometry
Current focus

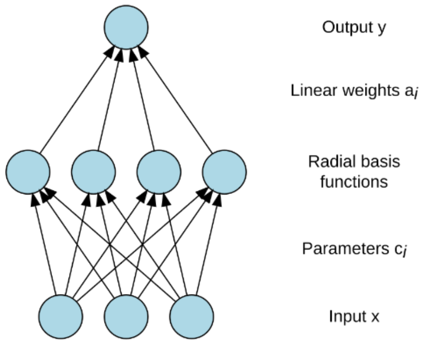
- Geometry represented as $d(\hat{\boldsymbol{n}}, V)$
  - Distance from surface to origin along acceleration vector
- Analytical solution (e.g. TankCuboid), or ...
- Use machine learning to approximate $d(\hat{\boldsymbol{n}}, V)$

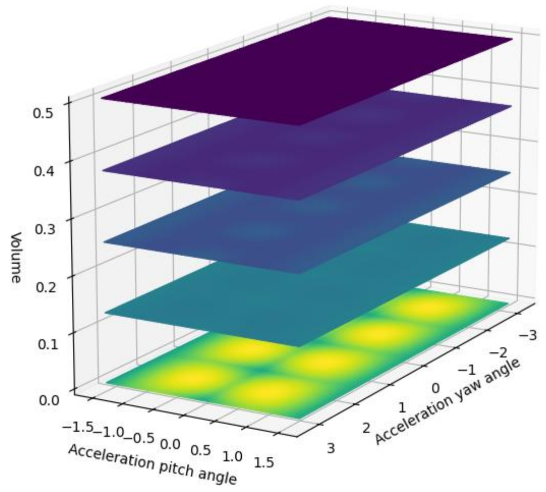


Geometry via ML

Current focus

- Learn $d(\hat{\boldsymbol{n}}, V)$ from training data
- Our focus has been on Radial Basis Functions (RBFs)
- Training data can be generated with CAD software



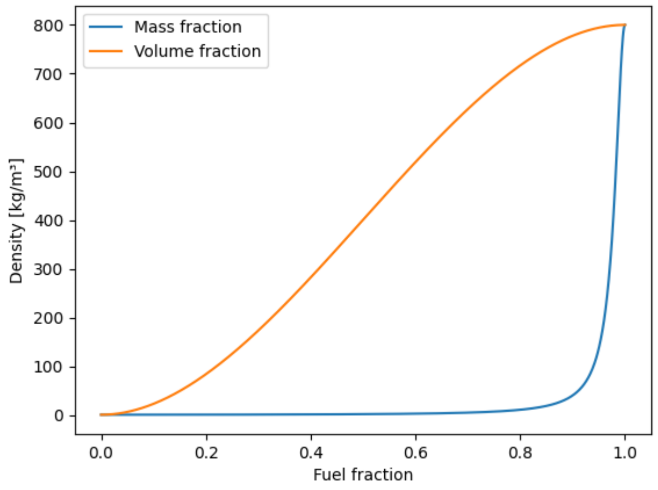


Displacement function for a cubical tank

Lind, I., Oprea, A., & Aeronautics, S. A. A. B. (2012, September). Detailed geometrical information of aircraft fuel tanks incorporated into fuel system simulation models. In *Proceedings of the 9th International MODELICA Conference, Munich, Germany* (pp. 3-5).

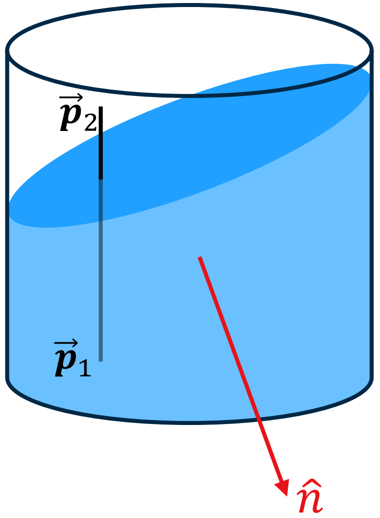
Tank Models – smooth transition
Current focus

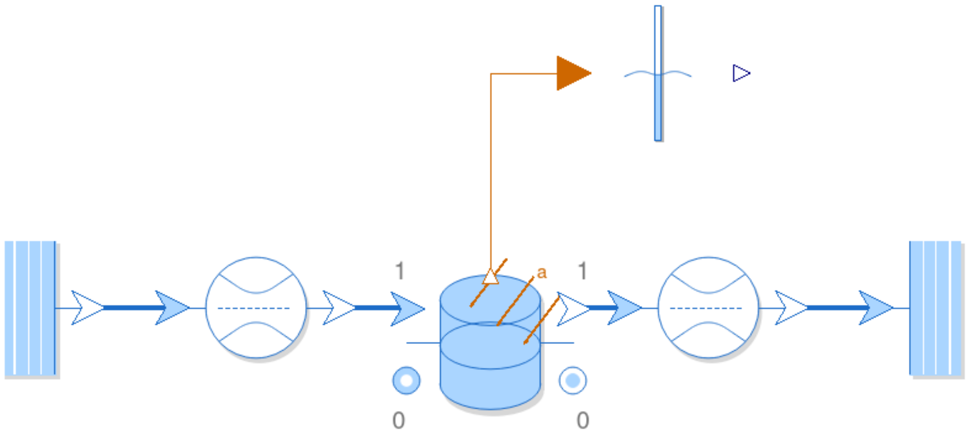
- Current implementation: smooth transition w.r.t mass fraction
  - 0.1% air by weight is ~50% by volume
- **Generally:** Medium density should change at most as quickly as mass flow
- **Potential solution:** mix by volumetric fraction instead of by mass fraction

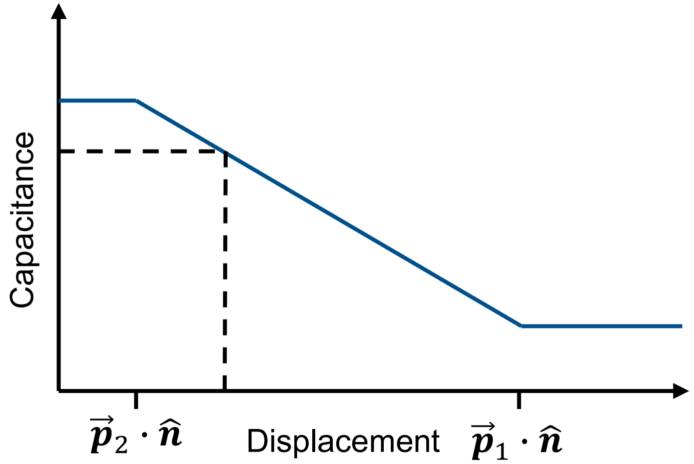


Probes, sensors
Current focus

- Pressure sensors, level sensors, float valves
  - Currently possible to model physically
  - Outlet at position of sensor/valve
- Capacitance probes (**WIP**)
  - Capacitance linear (affine) w.r.t immersed level
  - Special case: probe parallel to surface







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Tool support

- Multiple Modelica tools used at Saab: Dymola, SystemModeler, OpenModelica
- OpenModelica has a few minor issues:
  - CentrifugalPump
  - Sensors and missing media properties

Conclusions
Remaining challenges

ThermofluidStream is easy to work with, and to create new models for

Most components for FS modeling, throughout the life-cycle phases, are available

Remaining challenges & future work:

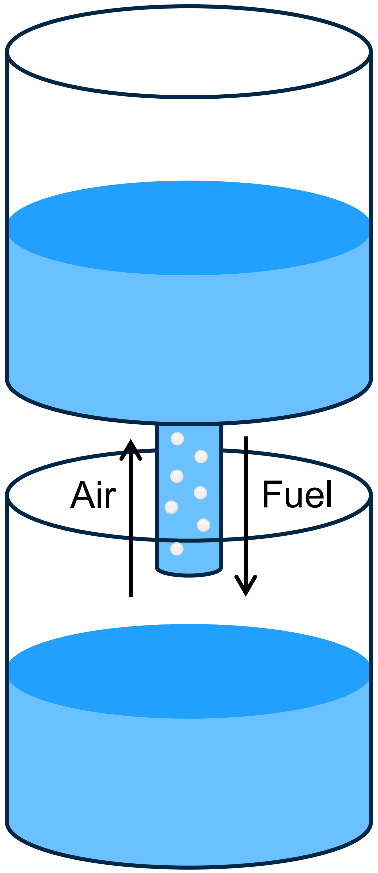
Ejector model with reverse flow regimes

Simultaneous bidirectional flow of air and fuel

- Experimental support exists, **large** increase in simulation time

Fuel sloshing

- Difficult to model, even for simple cases



Thank you!

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