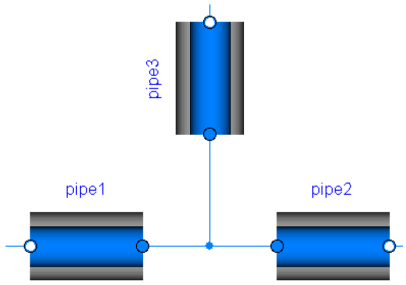
Overview and Rational for Modelica Stream Connectors

June 11, 2008



Revisions:

May 25, 2008	by Martin Otter (DLR). First version. Presented at 57th Modelica Design Meeting
June 9, 2008	by Martin Otter (DLR): Considerably improved version. Presented at EUROSYSLIB WP5.3 meeting
June 11, 2008	by Martin Otter (DLR): Newly structured and considerably improved (after EUROSYSLIB meeting)

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Contents

Part A Overview

At the 57th Modelica design meeting (May 25-28, 2008) a new fundamental type of connector variables "**stream**" was introduced for the next Modelica Language Specification Version 3.1, because the two standard types of port variables used in all component oriented modeling systems

potential/flow, across/through, effort/flow variables

are not sufficient to model flow of matter in a reliable way.

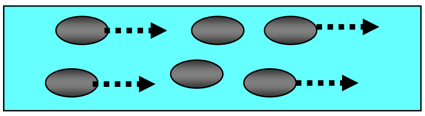
Modelica_Fluid 1.0 RC 1 is heavily based on this new concept.

These slides give an introduction in to this new connector type and provide a rational why it is introduced and the benefits of the concept.

1. Stream Variables and Stream Operators

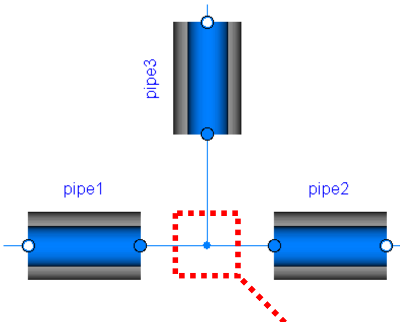
Purpose

- Reliable handling of convective mass and energy transport in thermo-fluid systems with bi-directional flow of matter.



(convective)
transport of matter

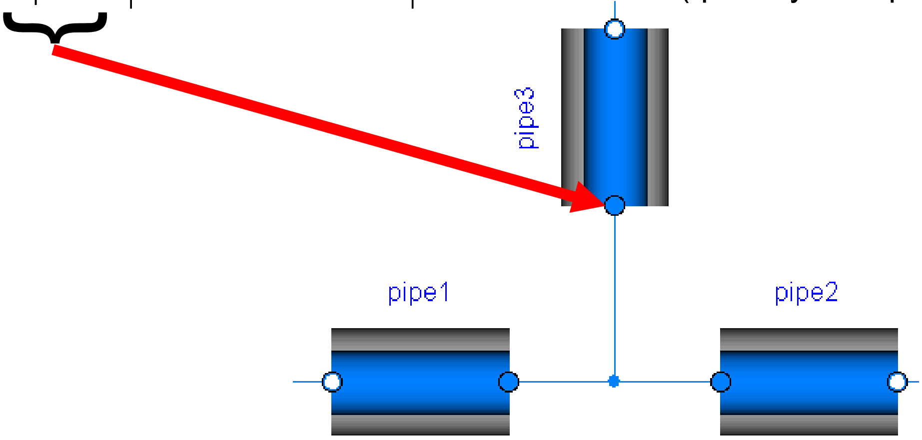
- Relevant boundary conditions and balance equations are fulfilled in a connection point.



mass and energy balance fulfilled
in the idealized connection point

Examples of an interface for fluid components

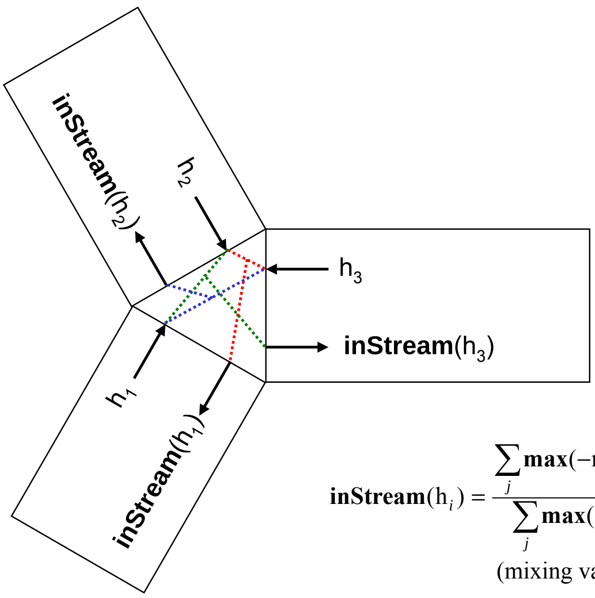
p	absolute pressure	**potential** variable
m_flow	mass flow rate	**flow** variable (describes transport of matter)
h	specific enthalpy	**stream** variable (quantity transported with matter)
X_i	mass fraction	**stream** variable (quantity transported with matter)



A **stream** variable h_i of a connector i is associated with
(a) a <u>flow</u> variable m_flow ("$0 = \Sigma$ m_flow$_i$") and
(b) a <u>stream balance</u> equation ("$0 = \Sigma$ m_flow$_i$*<<u>upstream</u> value of h_i>")

<u>Reliable</u> handling of bi-directional flow:

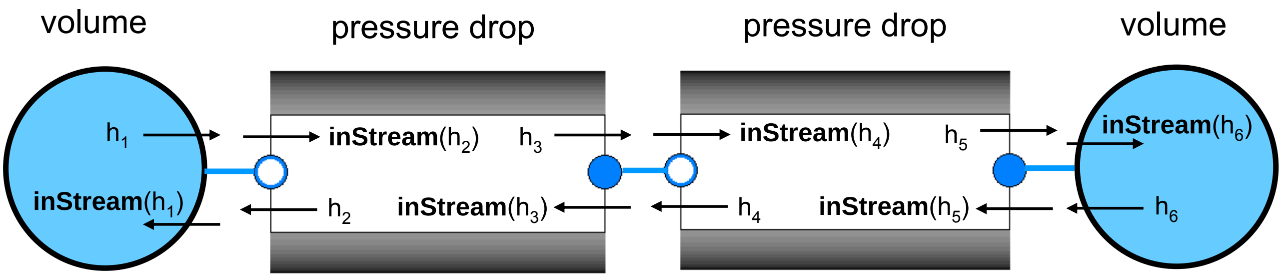
	value of stream variable h_i in connector i
h_i	if flow from component **to connection point** (m_flow$_i$ ≤ 0)
inStream(h_i)	if flow from connection point **to component** (m_flow$_i$ > 0
actualStream(h_i)	for both flow directions (= **if** m_flow$_i$ > 0 **then instream**(h_i) **else** h_i) only to be used when absolutely necessary(!)



$$\textbf{inStream}(h_i) = \frac{\sum_j \textbf{max}(-\text{m\_flow}_j, \varepsilon)\cdot h_j}{\sum_j \textbf{max}(-\text{m\_flow}_j, \varepsilon)} \quad \left(j \neq i,\ \text{m\_flow.min}_j < 0\right)$$

(mixing value for m_flow$_i$ > 0)

Example of a volume – pressure drop network



inStream(h1) = h2 = **inStream**(h3) = h4 = **inStream**(h5) = h6
inStream(h6) = h5 = **inStream**(h4) = h3 = **inStream**(h2) = h1

Energy balance in volume 1:

der(U_1) = m_flow$_1$***actualStream**(h_1)
= m_flow$_1$*(**if** m_flow$_1$ > 0 **then inStream**(h_1) **else** h_1)
= m_flow$_1$*(**if** m_flow$_1$ > 0 **then** h_6 **else** h_1)

2. Modeling with Streams

Connector definition:

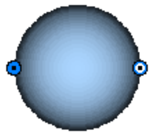
```
connector FluidPort
  SI = Modelica.SIunits;
  SI.AbsolutePressure        p            "Pressure in connection";
  flow   SI.MassFlowRate     m_flow       "Mass flow rate";
  stream SI.SpecificEnthalpy h_outflow    "h if m_flow <= 0";
  stream SI.MassFraction     X_outflow[nX] "X if m_flow <= 0";
end FluidPort;
```

If a **connector** has one or more **stream** variables, exactly **one** (scalar) **flow** variable must be present which is the flow associated with all stream variables.

Modeling with stream variables is very simple (see following examples)!

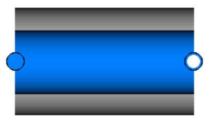
For notational convenience, the equations for the mass fractions X are not shown in the following examples.

Example: Mixing Volume



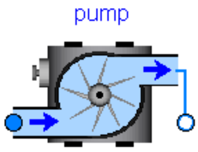
```
model MixingVolume "Volume that mixes two flows"
  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium;
  FluidPort port_a, port_b;
  parameter Modelica.SIunits.Volume V "Volume of device";
  Modelica.SIunits.Mass             m "Mass in device";
  Modelica.SIunits.Energy           U "Inner energy in device";
  Medium.BaseProperties medium(preferredMediumStates=true);
equation
  // Definition of port variables
  port_a.p         = medium.p;
  port_b.p         = medium.p;
  port_a.h_outflow = medium.h;
  port_b.h_outflow = medium.h;

  // Mass and energy balance
  m = V*medium.d;
  U = m*medium.u;
  der(m)  = port_a.m_flow + port_b.m_flow;
  der(U)  = port_a.m_flow*actualStream(port_a.h_outflow) +
            port_b.m_flow*actualStream(port_b.h_outflow);
end MixingVolume;
```


Example: Isenthalpic fluid transport



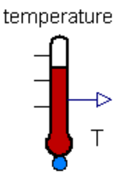
```
model IsenthalpicFlow "No energy storage/losses, e.g. pressure drop, valve, ..."
  replaceable package Medium=Modelica.Media.Interfaces.PartialMedium;
  FluidPort port_a, port_b:
  Medium.ThermodynamicState port_a_state_inflow "State at port_a if inflowing";
  Medium.ThermodynamicState port_b_state_inflow "State at port_b if inflowing";
equation
  // Medium states for inflowing fluid
  port_a_state_inflow = Medium.setState_phX(port_a.p,
                                            inStream(port_a.h_outflow));
  port_b_state_inflow = Medium.setState_phX(port_b.p,
                                            inStream(port_b.h_outflow));
  // Mass balance
  0 = port_a.m_flow + port_b.m_flow;

  // Instantaneous propagation of enthalpy flow between the ports with
  // isenthalpic state transformation (no storage and no loss of energy)
  port_a.h_outflow = inStream(port_b.h_outflow);
  port_b.h_outflow = inStream(port_a.h_outflow);

  // (Regularized) Momentum balance
  port_a.m_flow = f(port_a.p, port_b.p,
                    Medium.density(port_a_state_inflow),
                    Medium.density(port_b_state_inflow));
end IsenthalpicFlow;
```

Example: Isentropic fluid transport




```
model IsenthalpicFlow "No energy storage, e.g. pump, heat losses, ..."
  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium;
  FluidPort port_a, port_b:
  Medium.ThermodynamicState port_a_state_inflow "State at port_a if inflowing";
  Medium.ThermodynamicState port_b_state_inflow "State at port_b if inflowing";
  Modelica.SIunit.Power     P_ext "Energy flow via other connectors"
equation
  // Medium states for inflowing fluid
  port_a_state_inflow = Medium.setState_phX(port_a.p, inStream(port_a.h_outflow));
  port_b_state_inflow = Medium.setState_phX(port_b.p, inStream(port_b.h_outflow));

  // Mass balance
  0 = port_a.m_flow + port_b.m_flow;

  // Instantaneous propagation of enthalpy flow between the ports with
  // isentropic state transformation
  port_a.h_outflow = Medium.isentropicEnthalpy(port_a.p,inStream(port_b.h_outflow));
  port_b.h_outflow = Medium.isentropicEnthalpy(port_b.p,inStream(port_a.h_outflow));

  // Energy balanced to compute energy flow exchanged with other ports
   0 = P_ext + port_a.m_flow*actualStream(port_a.h_outflow)
             + port_b.m_flow*actualStream(port_b.h_outflow);

  // (Regularized) Momentum balance
  port_a.m_flow = f(port_a.p, port_b.p, Medium.density(port_a_state_inflow),
                                        Medium.density(port_b_state_inflow));
end IsenthalpicFlow;
```


Example: Temperature sensor

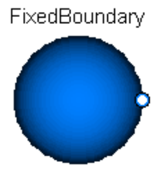



```
model TemperatureSensor "Ideal temperature sensor"
  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium;
  FluidPort port(m_flow(min=0)); // No flow out of sensor ever
  Modelica.Blocks.Interfaces.RealOutput T "Upstream temperature";
equation
  T = Medium.temperature(Medium.setState_phX(port.p, inStream(port.h_outflow));
  port.m_flow     = 0;
  port.h_outflow = Medium.specificEnthalpy(Medium.setState_pTX(
                        Medium.reference_p, Medium.reference_T));
                    // This value will never be used, since m_flow(min=0),
                    // but it will show up in the plot window.
end TemperatureSensor;
```

Setting "m_flow.min=0" is very important, in order that the temperature sensor has no influence on the stream that it measures, if <u>all mass flow rates are zero</u>; since then "**max**(-port.m_flow,ε) = 0" in the **inStream**(..)-operators of the connected ports!!!

$$\mathbf{inStream}(\mathrm{h}_i) = \frac{\sum_j \mathbf{max}(-\mathrm{m\_flow}_j, \varepsilon)\cdot \mathrm{h}_j}{\sum_j \mathbf{max}(-\mathrm{m\_flow}_j, \varepsilon)} \quad \left(j \neq i,\ \mathrm{m\_flow.min}_j < 0\right)$$

Example: Infinite Reservoir




```
model FixedBoundary_pT "Infinite reservoir with fixed pressure and temperature"
  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium;
  FluidPort port;
  parameter Medium.AbsolutePressure p "Boundary pressure";
  parameter Medium.Temperature      T "Boundary temperature";
equation
  port.p         = p;
  port.h_outflow = Medium.specificEnthalpy(Medium.setState_pTX(p, T));
end FixedBoundary_pT;
```


Part B Rational

The following slides

- provide a rational, why reliable bi-directional flow modeling requires a third type of connector variable (streams),
- discusses details of the connection semantics of streams,
- shows why stream connectors lead to reliable models.

3. Basic Problems of Fluid Connectors

Desired connector for bi-directional flow of matter. The intensive quantities transported with the matter (like h) have the newly introduced "**stream**" prefix:

```
connector FluidPort
  import SI = Modelica.SIunits;
  SI.AbsolutePressure         p        "Pressure in connection point";
  flow    SI.MassFlowRate     m_flow   "Mass flow rate";
  stream SI.SpecificEnthalpy h        "Specific enthalpy";
end FluidPort;
```

Observation

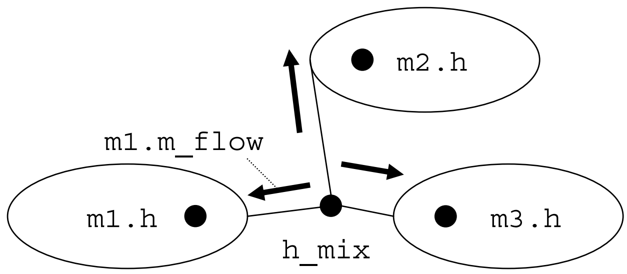
This is the most simplest connector description form for the desired class of models (independently how the connected components are described, e.g. lumped, discretized PDE, PDE, ...). It is very unlikely that a "simpler" connector exists.

Goal

Define connection semantic of stream variables, so that the balance equations for stream variables in an infinitesimal small connection point are fulfilled and the equations can be solved reliably.

Central Question: What is the meaning of a stream variable, such as "h"?

Balance equations of stream variables for 3 connected components (independently how the components are described, e.g. lumped, PDE, ...)




```
(1)  0 = m1.m_flow*(if m1.m_flow > 0 then h_mix else m1.h) +
         m2.m_flow*(if m2.m_flow > 0 then h_mix else m2.h) +
         m3.m_flow*(if m3.m_flow > 0 then h_mix else m3.h)
(2)  0 = m1.m_flow + m2.m_flow + m3.m_flow
```

From the balance equations, it seems natural that the stream variables are one of the occurring variables, e.g., `h_mix` or `m1.h`

but: then, the result will be of the form:

```
h_mix = if m1.m_flow > 0 then ... else ...
m1.h  = if m1.m_flow > 0 then ... else ...
```

e.g. for 2 connected components:

```
h_mix = if m1.m_flow > 0 then m2.h else m1.h
```

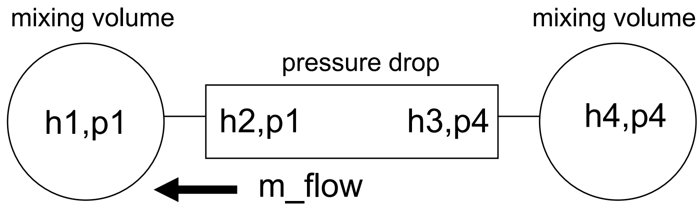
this means that `m1,h, m2.h, h_mix` etc. are computed by equations that contain **if**-clauses which depend on the **mass flow rate**.

If algebraic systems of equations occur (due to initialization, or ideal mixing, or pressure drop components directly connected together etc.), then these equation systems, inevitably, have unknowns that depend on the unknown mass flow direction, i.e., **nasty non-linear equation systems** occur that are difficult to solve (since Boolean unknowns as iteration variables)!!!

The issue appears even in the **most simplest case** of

MixingVolume – PressureDrop – MixingVolume

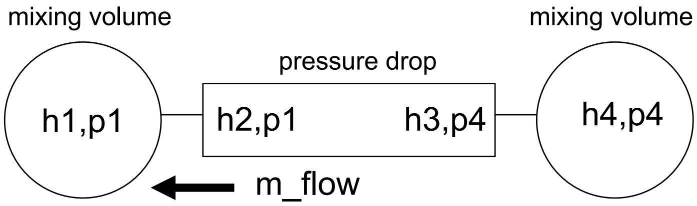
connection, if the mass flow rate in the pressure drop does not only depend on pressure, but also on density as a function of the medium state:




```
    h2 = if m_flow > 0 then h4 else h1
    h3 = h2;          // !!!!!
    d2 = f1(p1,h2)    // density
    d3 = f1(p4,h3)
m_flow = f2(p1, p4, d2, d3)
```

Note: Even for the most simplest case (volume – pressure drop – volume), a **nasty non-linear equation system** appears, since `m_flow = f2(..., m_flow > 0);`
Can sometimes be fixed by replacing "`m_flow > 0`" with "`p4 - p1 > 0`"

Additionally, <u>every pressure drop</u> component is **not differentiable** at **m_flow = 0**. If non-linear equation systems occur, then this system is not differentiable at a critical point, and then every non-linear solver has difficulties.




```
     h2  = if m_flow > 0 then h4 else h1
     h3  = h2;          // !!!!!
     d2  = f1(p1,h2)    // density
     d3  = f1(p4,h3)
 m_flow  = f2(p1, p4, d2, d3)
```

Major problem:
Independently of the flow direction: `h3 = h2`

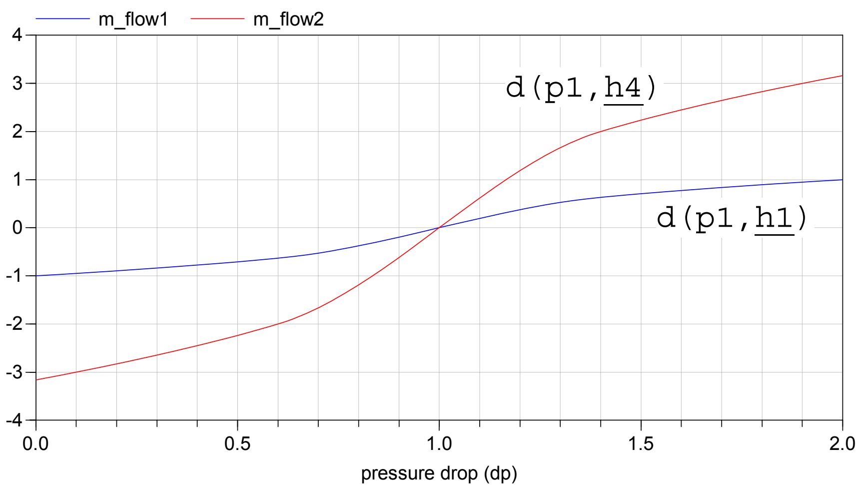
```
m_flow > 0:  m_flow = f2(..., d2(p1,h4), d3(p4,h4));
m_flow < 0:  m_flow = f2(..., d2(p1,h1), d3(p4,h1));
```

However (see next slides): `f2(..)` must be a function of `d2(p1,h1), d3(p1,h4)` !!!

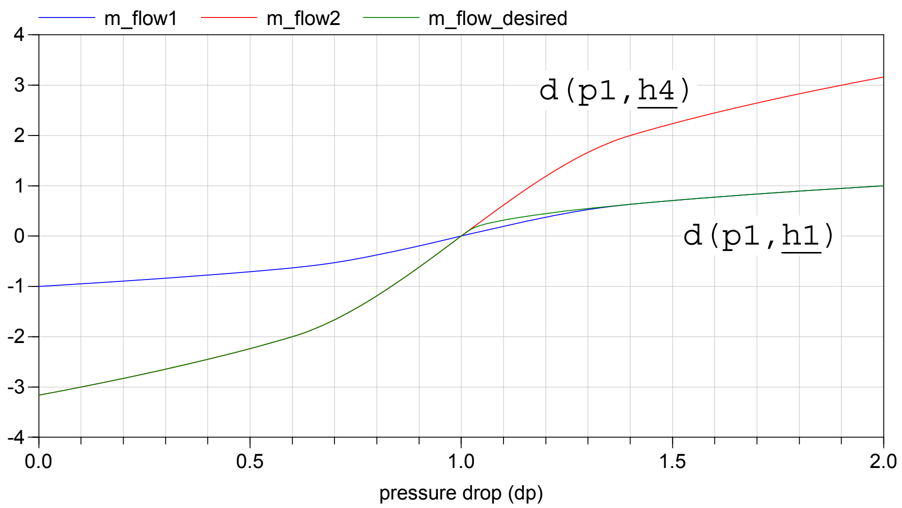
When m_flow > 0, dp > 0: The "blue" curve (m_flow1) is computed.
When m_flow < 0, dp < 0: The "red" curve (m_flow2) is computed.

When m_flow changes from positive to negative, the interpolation jumps from curve "blue" to "red". This means, that m_flow is **not differentiable** at **m_flow = 0**.

If m_flow appears in a non-linear equation system, this is not good, because the pre-requisite of a non-linear solver is not fulfilled in the critical point at m_flow = 0!!!!

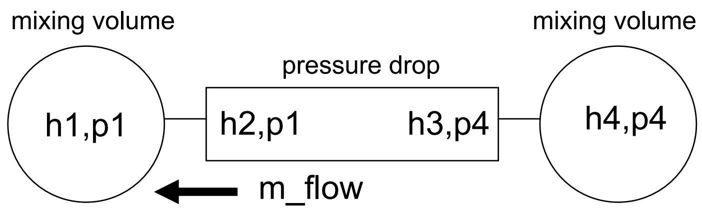


Correct treatment: m_flow = f2(..) is a function of d2(p1,h1), d3(p1,h4) !!!



In order that the correct f2(..) function is used ("green" curve),
the "density" of the "actual" flow (`m_flow > 0`) and
the "density" of the "reversed flow" (`m_flow < 0`) are needed
at the **same time instant**!!!! Only then, regularization around m_flow = 0 is possible, leading to a smooth characteristic.

Summary:
It is impossible to arrive at reliable, bi-directional flow models, if the actual intensive quantities (like h_mix, h1, h2, ...) are used in the connector equations.



Note, the only way to avoid the identified problems is to **not** compute `h_mix, m1.h`, etc. Instead:

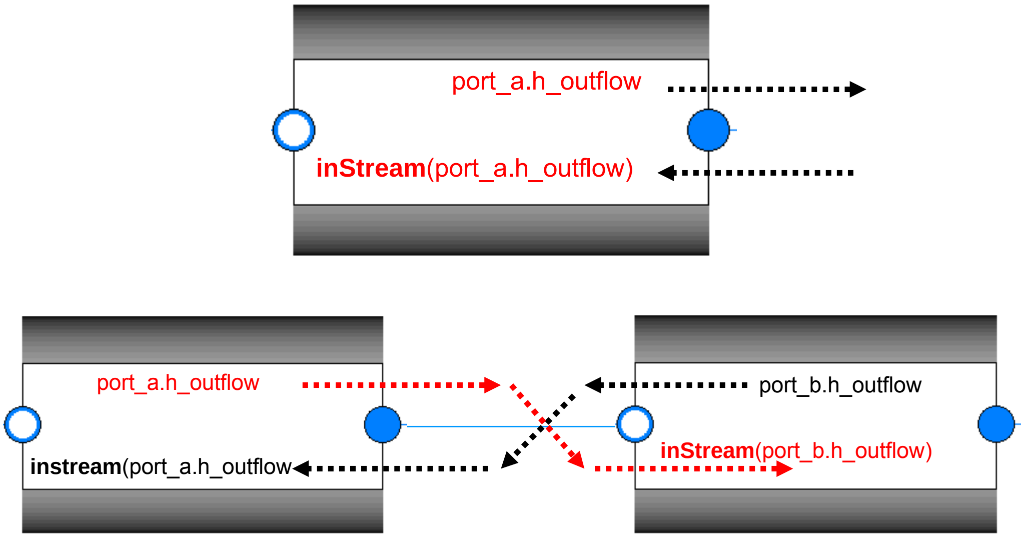
```
d2_outflow = f1(p1,h4)   // flow from h4 to h1
d3_outflow = f1(p4,h1)   // flow from h1 to h4
    m_flow = f2(p1, p4, d2_outflow, d3_outflow)
```

4. Stream Connection Semantics

Central idea:

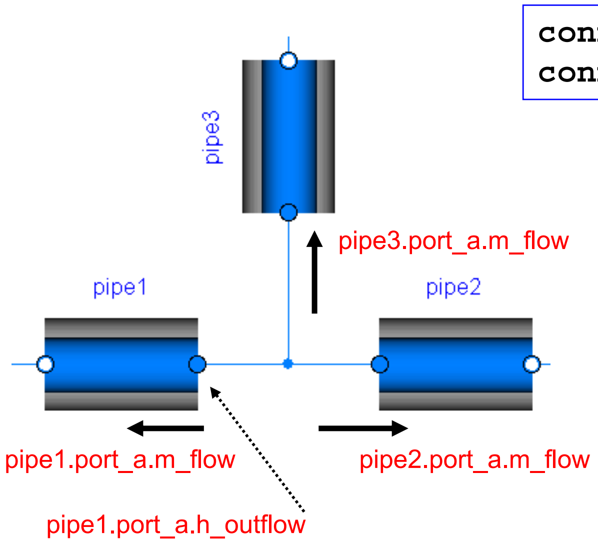
a) compute value for "outflow" and

b) inquire value for "inflow" with operator "**inStream**(..)"



Basic connector definition

```
connector FluidPort
  SI = Modelica.SIunits;
  SI.AbsolutePressure        p         "Pressure in connection point";
  flow   SI.MassFlowRate      m_flow    "Mass flow rate";
  stream SI.SpecificEnthalpy h_outflow "h close to port if m_flow < 0";
end FluidPort;
```




```
connect(pipe1.port_a, pipe2.port_b);
connect(pipe1.port_a, pipe3.port_b);
```

```
pipe1.port_a.p = pipe2.port_a.p
pipe1.port_a.p = pipe3.port_a.p
0 = pipe1.port_a.m_flow +
    pipe2.port_a.m_flow +
    pipe3.port_a.m_flow
```

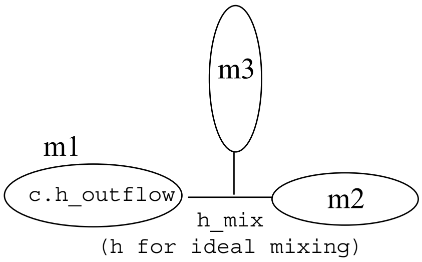
<ins>No connection</ins> equations are generated for stream variables (!)

model : m1,m2,m3;
connector: c;
flow : m_flow
stream : h_outflow

balance equations

```
(1) 0 = m1.c.m_flow*(if m1.c.m_flow > 0 then h_mix else m1.c.h_outflow) +
        m2.c.m_flow*(if m2.c.m_flow > 0 then h_mix else m2.c.h_outflow) +
        m3.c.m_flow*(if m3.c.m_flow > 0 then h_mix else m3.c.h_outflow)
(2) 0 = m1.c.m_flow + m2.c.m_flow + m3.c.m_flow
```

```
(1) 0 = max(m1.c.m_flow,0)*h_mix - max(-m1.c.m_flow,0)*m1.c.h_outflow +
        max(m2.c.m_flow,0)*h_mix - max(-m2.c.m_flow,0)*m2.c.h_outflow +
        max(m3.c.m_flow,0)*h_mix - max(-m3.c.m_flow,0)*m3.c.h_outflow
(2) 0 =   max( m1.c.m_flow,0) + max( m2.c.m_flow,0) + max(m3.c.m_flow,0)
        - max(-m1.c.m_flow,0) - max(-m2.c.m_flow,0) - max(m3.c.m_flow,0)
```




```
(3) h_mix = (max(-m1.c.m_flow,0)*m1.c.h_outflow +
             max(-m2.c.m_flow,0)*m2.c.h_outflow +
             max(-m3.c.m_flow,0)*m3.c.h_outflow) /
            (max(m1.c.m_flow,0) +
             max(m2.c.m_flow,0) +
             max(m3.c.m_flow,0))
```

mass balance

```
(4) h_mix = (max(-m1.c.m_flow,0)*m1.c.h_outflow +
             max(-m2.c.m_flow,0)*m2.c.h_outflow +
             max(-m3.c.m_flow,0)*m3.c.h_outflow) /
            (max(-m1.c.m_flow,0) +
             max(-m2.c.m_flow,0) +
             max(-m3.c.m_flow,0))
```



```
(4) h_mix = (max(-m1.c.m_flow,0)*m1.c.h_outflow +
             max(-m2.c.m_flow,0)*m2.c.h_outflow +
             max(-m3.c.m_flow,0)*m3.c.h_outflow) /
            (max(-m1.c.m_flow,0) +
             max(-m2.c.m_flow,0) +
             max(-m3.c.m_flow,0))
```

Definition:

inStream(m1.c.h_outflow) = h_mix for m1.c.m_flow > 0

Reason:

This definition prepares for the changing flow direction at `m1.c.m_flow = 0`:
If only `m1.c.m_flow` is changing the flow direction, then
`h_mix` is **discontinuous** at `m1.c.m_flow = 0`.

However,
`h_mix for m1.c.m_flow > 0` is **continuous** at `m1.c.m_flow = 0`
since m1.c.h_outflow does not appear in the equation, because for inflowing flow, this variable does not influence the mixing and the same formula is used also for the reversed direction!!!

```
(4) h_mix = (max(-m1.c.m_flow,0)*m1.c.h_outflow +
             max(-m2.c.m_flow,0)*m2.c.h_outflow +
             max(-m3.c.m_flow,0)*m3.c.h_outflow) /
            (max(-m1.c.m_flow,0) +
             max(-m2.c.m_flow,0) +
             max(-m3.c.m_flow,0))
```

Definition: **inStream**(m1.c.h_outflow) = h_mix for m1.c.m_flow > 0

```
(5) inStream(m1.c.h_outflow) = (max(-m2.c.m_flow,0)*m2.c.h_outflow +
                                max(-m3.c.m_flow,0)*m3.c.h_outflow) /
                               (max(-m2.c.m_flow,0) + max(-m3.c.m_flow, 0))
                             ≈ (max(-m2.c.m_flow,ε)*m2.c.h_outflow +
                                max(-m3.c.m_flow,ε)*m3.c.h_outflow) /
                               (max(-m2.c.m_flow,ε) + max(-m3.c.m_flow,ε))
```

For 2 connections:

```
(6) inStream(m1.c.h_outflow) = (max(-m2.c.m_flow,0)*m2.c.h_outflow /
                                max(-m2.c.m_flow,0)
                             = m2.c.h_outflow
```

For 3 connections with m3.c.m_flow.min=0 (One-Port Sensor):

```
(7) inStream(m1.c.h_outflow) = m2.c.h_outflow
(8) inSteram(m3.c.h_outflow) = (max(-m1.c.m_flow,0)*m1.c.h_outflow +
                                max(-m2.c.m_flow,0)*m2.c.h_outflow) /
                               (max(-m1.c.m_flow,0) + max(-m2.c.m_flow, 0))
```


If all mass flow rates are **zero**, the stream balance equation is identically fulfilled, independently of the values of h_mix, and mi.c.h_outflow. Therefore, there are an **infinite number of solutions**.

The basic idea is to approximate the "**max(..)**" function to avoid this case:

```
(5) inStream(m1.c.h_outflow) = (max(-m2.c.m_flow,0)*m2.c.h_outflow +
                                max(-m3.c.m_flow,0)*m3.c.h_outflow) /
                               (max(-m2.c.m_flow,0) + max(-m3.c.m_flow, 0))

                             ≈ (max(-m2.c.m_flow,ε)*m2.c.h_outflow +
                                max(-m3.c.m_flow,ε)*m3.c.h_outflow) /
                               (max(-m2.c.m_flow,ε) + max(-m3.c.m_flow,ε))
```

Then a unique solution of this equation always exists.

If all mass flow rates are identically to **zero**, the result is the **mean value** of the involved specific enthalpies:

```
(6) inStream(m1.c.h_outflow) ≈ (max(-m2.c.m_flow,ε)*m2.c.h_outflow +
                                max(-m3.c.m_flow,ε)*m3.c.h_outflow) /
                               (max(-m2.c.m_flow,ε) + max(-m3.c.m_flow,ε))
                             = (ε*m2.c.h_outflow + ε*m3.c.h_outflow) / (ε + ε)
                             = (m2.c.h_outflow + m3.c.h_outflow) / 2
```

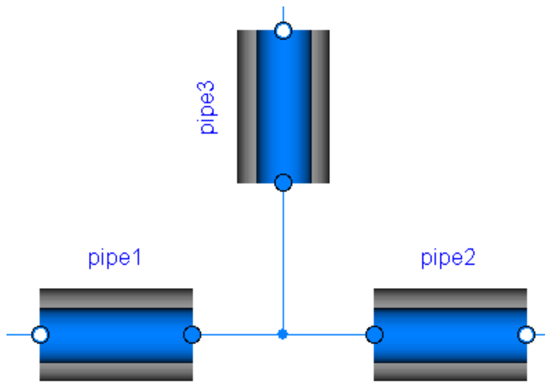
The actual regularization is a bit more involved, in order that

- an approximation is only used, if **all** mass flow rates are small,
- the characteristic is continuous and **differentiable**
  (max(.., ε) is continuous but **not** differentiable)

```
// Actual regularization for small mass flow rates

// Determine denominator s for exact computation
s := sum( max(-mj.c.m_flow,0) )

// Define a "small number" eps (nominal(v) is the nominal value of v)
eps := relativeTolerance*min(nominal(mj.c.m_flow))

// Define a smooth curve, such that alpha(s>=eps)=1 and alpha(s<=0)=0
// (using a polynomial of 3rd order)
alpha := smooth(1, if s > eps then 1 else
                   if s > 0   then (s/eps)^2*(3-2*(s/eps)) else 0);

// Define function positiveMax(v) as a linear combination of max(v,0)
// and of eps along alpha
positiveMax(-mj.c.m_flow) := alpha*max(-mj.c.m_flow,0) + (1-alpha)*eps;

// Use "positiveMax(..)" instead of "max(.., eps)" in the
// inStream(..) definition!
```

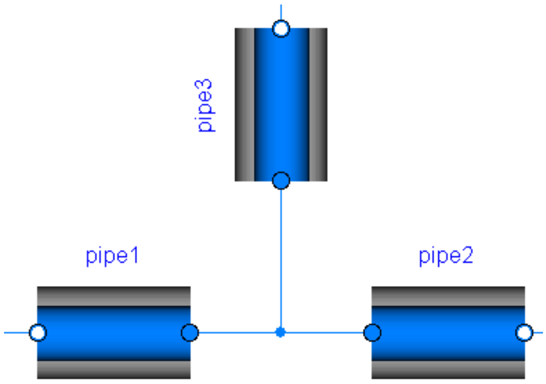

5. Reliable Handling of Ideal Mixing

reference problem



- "DryAirNasa" (ideal gas with f(p,T)) and
  "FlueGasSixComponents" (mixture of ideal gases with 6 substances)
- Detailed pipe friction correlations for the laminar and turbulent flow regimes
- Ideal mixing point (no volume) in the connection point.

All the details are described in a report from M. Sielemann and M. Otter.
Only the major results are presented on the following slides.



(Note: with a volume in the connection point there would be 2+6=8 state variables, i.e., an implicit DAE solver would have 8 iteration variables).

Number of iteration variables for "FlueGasSixComponents"
(mixture of ideal gases with 6 substances)

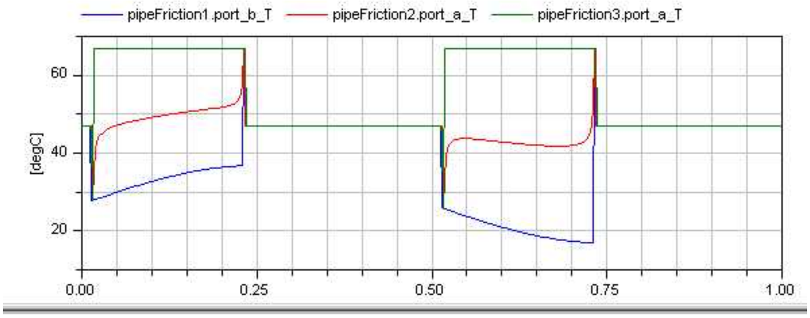
22	Modelica_Fluid (previous version; non-smooth iteration variables; no sim.)
6	ThermoPower (non-smooth iteration variables)
3	Modelica_Fluid (new version with "stream"; smooth iteration variables)

Basic (previous) form of "pressure drop" component:

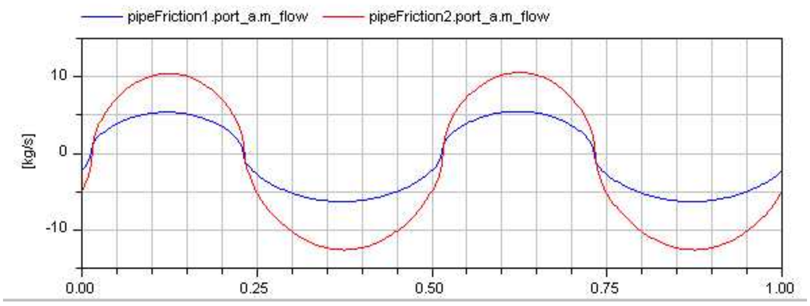
```
  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium;
  Medium.BaseProperties medium_a_inflow;
  Medium.BaseProperties medium_b_inflow;
equation
  medium_a_inflow.p = port_a.p;
  medium_b_inflow.p = port_b.p;
  medium_a_inflow.h = inStream(port_a.h_outflow);
  medium_b_inflow.h = inStream(port_b.h_outflow);
  port_a.h_inflow   = medium_a_inflow.h;
  port_b.h_inflow   = medium_b_inflow.h;
  port_a_d_inflow   = medium_a_inflow_d;
  port_b_d_inflow   = medium_b_inflow_d;;
```

If medium is not f(p.h), a non-linear equation system appears, in order to compute `medium_a_inflow.h` from `medium_a_inflow.T` (and from the pressure).
For an ideal mixing point (or any other non-linear equation system), a tool will therefore select T as iteration variable.

Severe disadvantage: Temperature is discontinuous and therefore the iteration variable is discontinuous!!!



T as iteration variable (<u>discontinuous</u>)
-> at m_flow = 0, jump in iteration variable; every non-linear solver has difficulties with this.



m_flow as iteration variable (<u>continuous</u>)

New form of "pressure drop" component:

```
  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium;
equation
  port_a.h_outflow     = inStream(port_b.h_outflow);
  port_b.h_outflow     = inStream(port_a.h_outflow);
  port_a_state_inflow = Medium.setState_phX(
                             port_a.p, inStream(port_a.h_outflow),...);
  port_b_state_inflow = Medium.setState_phX(
                             port_b.p, inStream(port_b.h_outflow),...);
  port_a_inflow = Medium.density(port_a_state_inflow);
  port_b_inflow = Medium.density(port_b_state_inflow);
```

If medium is <u>not</u> f(p.h), no (explicit) non-linear equation system appears, since the medium state is computed from the known port properties.

However, the function "setState_phX" solves internally a non-linear equation system (with Brents algorithm; a fast and very reliable algorithm to solve one non-linear algebraic equation in one unknown).

A tool can now compute all variables in a point with N connections from

N-1 mass flow rates and **1 pressure**

in an explicit forward sequence and therefore selects these variables as iteration variables (and these variables are always continuous):

1. The N-th mass flow rate is computed from the mass balance
2. The port-specific mixing enthalpies (h_mix(m_flow_i = 0)) can be computed, since they depend only on known variables (enthalpies in the volumes and the mass flow rates).
3. The medium states can be computed via Medium.setState_phX(..), since p,h,X are known now.
4. All medium properties can be computed from the medium state, especially the density.
5. Via the momentum balance, the mass flow rates can be computed (= residue equations).

Analysis does also hold for **initialization**: With this approach, initialization will work much better, since mass flow rates are selected as iteration variables. A default start value of zero for mass flow rates is often sufficient for the solver.

Summary

If the "streams" concept is used, and the pressure drop components are implemented as sketched in the previous slide, then an ideal mixing point with N connections gives rise to a non-linear system of algebraic equations (if N > 2 and no min-attributes are set) that has the following properties:

- The **number of iteration** variables is **N** (independent of the medium, and how many substances are in the medium).
- The **iteration variables** are **continuous** everywhere (since as iteration variables, N-1 mass flow rates and one pressure is used).
- The **iteration variables** are in **most cases differentiable** (due to the definition of stream-variables and of the **inStream**(..) operator). The iteration variables are not differentiable, if all mass flow rates in an ideal mixing point become zero at the same time instant. If this is not the case, they are differentiable.
- **Default start** values of **zero** for the mass flow rates and for the pressure drop in the pressure drop components, are **good guess values** for the iteration variables (independent of the medium).

It can therefore be expected that a solution of the equation system is easy to compute by every reasonable non-linear equation solver.

6. Open Issues

- For a regular network of the usual "Volume – Pressure Drop – Volume" structure a **non-linear algebraic** equation in one unknown is present for every connector of a pressure drop component, if the medium states are **not p,h,X**. It seems possible to remove all these equation systems by "medium propagation" developed by Dynasim for the previous Modelica_Fluid version (not yet clear how to do it, but should be possible). This issue is not critical, because the equation is solved reliably. The only issue is to enhance efficiency.
- If components from discretized PDEs are connected together, it is not yet clear how to formulate the momentum balances at the "ends" of such components. A "clean" solution will split the **momentum balance** between two components in **two parts**. This results in one non-linear algebraic equation in one unknown (the pressure) for every connection point. Either this equation can be analytically solved, or a "non-clean" solution has to be used.

7. Status

- Detailed specification text for Modelica 3.1 available
- (Positive) voting for the <u>specification</u> text for inclusion in <u>Modelica 3.1</u>
- <u>Prototype</u> implementation in <u>Dymola</u> available (special Dymola 7 version)
- Modelica_Fluid library changed to new connector design (https://svn.modelica.org/Modelica_Fluid/branches/StreamConnector/)
- Detailed tests with sandbox libraries by Rüdiger Franke and Michael Sielemann
- All examples of Modelica_Fluid simulate without problems
- Initialization parameters removed from all pressure drop coefficients (no longer needed, since m_flow used as iteration variable; default of m_flow.start = 0 is a good guess value; a better one can be provided via a parameter)
- Some (minor) issues of Modelica_Fluid identified that shall be fixed until June 15. After fixing: release of "Modelica_Fluid 1.0 RC 1".
- <u>Plan</u>: Tests in EUROSYSLIB with <u>larger and realistic benchmarks</u>.

The tool requirements for "stream" support is very modest:

- No special symbolic transformation algorithms needed!
- Connection semantic is trivial:
  Generate no connection equation for stream variables
- The **inStream**(..) operator requires to analyze all corresponding stream-variables in a connection set (e.g. with respect to "min(..)" attributes).
  A tool could decide to only support 1:1 connections in the beginning.
  The **inStream**(..) operator is then trivial to implement.
- Inside/outside connections (= hierarchical connections) complicate issues a bit (similarly to flow-variables), but nothing serious

8. History and Contributors

- 2002:ThermoPower connectors by Francesco Casella
  (this is the basis of the stream connector concept)
- 2002: First version of Modelica_Fluid that is refined until 2008.
  Many basic concepts are from Hilding Elmqvist.
  It was never possible to make the library reliable.
- Jan. 2008: upstream(..) operator by Hilding Elmqvist
  (triggered the further development)
- Jan. 2008: new formulation of "ideal mixing" from Francesco Casella
  (this is the basis of the inStream(..) operator)
- March 2008: proposal of "stream" connectors by Rüdiger Franke
- April 2008: refined proposal by Rüdiger Franke & Martin Otter,
  prototype in Dymola by Sven Erik Mattsson,
  improved definition of inside/outside connector by Hans Olsson,
  test of the concept by Rüdiger Franke and Michael Sielemann,
  reformulation to improve the numerics by M. Sielemann and M. Otter,
  transformation of Modelica_Fluid to streams by M. Otter
- May 2008: final proposal developed by Modelica fluid group at the
  57th design meeting and (positive) vote for inclusion in Modelica 3.1.