Pneumatic library

The submodels in the Pneumatic library use the first and second law of thermodynamics.

The following assumptions are used:

- the velocity of gas is not supersonic,
- the flow is one-dimensional,
- the gas is considered to be a perfect, semi-perfect, or a real gas,
- the gravitational effect on the gas is not taken into account,
- the intensive variables, i.e. pressure and temperature, are assumed to be average values in the whole volume considered (lumped modeling),
- the kinetic energy is ignored in chamber submodels,
- reversible thermodynamic transformations are used in the orifice submodels.

Perfect gas $$\frac{p}{\rho} = R \cdot T$$

where p is the absolute pressure [*PaA*], ρ is the density [kg/m^3], R is the gas constant [*J/kg/K*] and T is the temperature [*K*].

Specific heat capacities are constant.

Valid for low pressure, small temperature variations, far from saturation temperature. Example: dry air at ambient conditions.

Semi-perfect or Ideal gas

Similar equation, but specific heat capacities are temperature-dependent.

Valid for medium pressure, significant temperature variations, far from saturation temperature. Example: air in gas turbine.

Mixture of perfect or semi-perfect gases

Gas property mixtures are computed from the ratios of the various gaseous constituents.

Real gas $$\frac{p}{\rho} = Z \cdot R \cdot T$$

where Z is the compressibility factor [*null*].

Four models of real gas are available: van der Walls, Redlich-Kwong, Redlich-Kwong-Soave and Peng-Robinson.

The absolute viscosity, the constant-pressure specific heat, and the thermal conductivity of a gas is calculated using a 2nd order polynomial function of the temperature.

Real gases cannot be used in gas mixtures.

It is pointless to perform a simulation using the real gas submodel and selecting polytrophic model in pipe or volume submodels. Those computations will not take the real gas behavior into account.

Pneumatic library usage

There are two main types of components in the Pneumatic library:

- Capacitive components are the volumes in which the temperature and the pressure are computed from the enthalpy and mass flow rate inputs at their ports.

- Resistive components are those in which the enthalpy and mass flow rates are evaluated from the temperature and pressure inputs at their ports.

This implies that a pneumatic model is always built in such a way that a resistive element *R* is always connected to a capacitive element *C*.

Sometimes, calculations may be unusually slow because of a large number of discontinuities. This may be due to integration 'noise' where small variations of some state variables are being greatly amplified.
A reduced tolerance will reduce the noise and may cure the problem. A value such as 10^{-7} should be tried first. It is normally unsatisfactory to set values for the tolerance higher than 10^{-3} or lower than 10^{-12}.

Chambers

Polytrophic model: $\frac{p}{\rho^{\kappa}} = const.$ or $p^{1-\kappa} \cdot T^{\kappa} = const.$
(e.g. PNCH021)

With heat exchange (preferred): $\frac{dU}{dt} = \sum \dot{m}_i \cdot h_i + \frac{dQ}{dt} + \frac{dW}{dt}$
(e.g. PNCH022)

The variation of internal energy *U* using the first law of thermodynamics applied to an open system.
$\dot{m}_i h_i$ is the enthalpy flow rate at a port (input is positive), $\frac{dQ}{dt}$ is the heat flow provided to or exiting from the volume, and $\frac{dW}{dt}$ is the work of the pressure forces.

This work is due to mechanical displacement when a piston is connected to the volume:

$$\frac{dW}{dt} = -p \cdot \frac{dV}{dt}$$

where $\frac{dV}{dt}$ is the volume variation.

Static and dynamic pressures

Using a perfect or semi-perfect gas assumption, the static pressure can be expressed as:

$$p_{stat} = p_{tot}\left(1 + \frac{v^2}{2 \cdot c_p \cdot T}\right)^{-\frac{\kappa}{\kappa-1}}$$

where v is the mean fluid velocity, c_p is the constant-pressure specific heat, T is the local temperature and κ is the specific heat ratio.

EXAMPLE

Modeling pneumatic orifices

In orifices and pipes, when the pressure ratio p_{down}/p_{up} is lower than 0.9999 the flow is assumed to be laminar.

PNAC001 - set the accuracy for orifices calculations 

This submodel enables to change this limit to 0.999, 0.99, or to a chosen value.
It can reduce the CPU time, but the results will be less precise.

Orifices are adiabatic components. The energy dissipated in them is all transferred to the fluid. Nothing is exchanged with outside.

Causality: the mass flow rate at port 1 is positive if the flow direction is from port 2 to port 1.

EXAMPLE

The kinetic energy of the upstream flow is ignored. The mass flow rate is a function of input pressures (absolutes) and temperatures:

$$\dot{m} = A \cdot c_q \cdot c_m \cdot \frac{p_{up}}{\sqrt{T_{up}}}$$

where p_{up} and T_{up} is the upstream pressure and temperature, c_m is the flow parameter.

The flow coefficient c_q is introduced to adjust the theoretical relationship to experiments. This coefficient is used to include extra losses due to local friction and loss of kinetic energy. It may represent frictional drag in pipes for instance, or local resistance due to changes in geometry or in flow direction.

Considering a perfect or semi-perfect gas behavior, the flow parameter is defined as:

$$c_m = \sqrt{\frac{2\kappa}{R(\kappa-1)}} \sqrt{\left(\frac{p_{dn}}{p_{up}}\right)^{\frac{2}{\kappa}} - \left(\frac{p_{dn}}{p_{up}}\right)^{\frac{\kappa+1}{\kappa}}} \quad if\ \frac{p_{dn}}{p_{up}} > p_{cr}\ (subsonic)$$

$$c_m = \sqrt{\frac{2\kappa}{R(\kappa-1)} \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}}} \quad if\ \frac{p_{dn}}{p_{up}} < p_{cr}\ (sonic)$$

When the flow is sonic, the flow parameter is constant and is only a function of the gas properties;
in subsonic flow the flow parameter is a function of the pressure ratio.

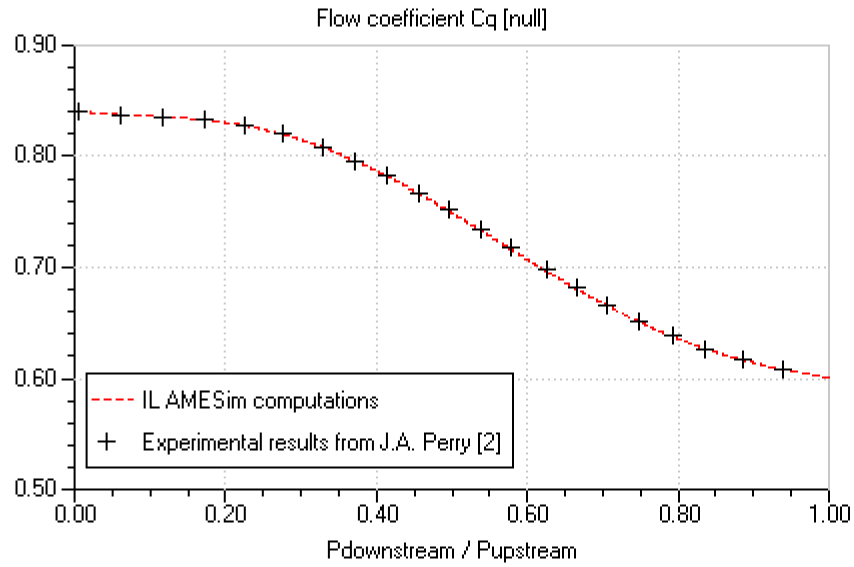
The critical pressure ratio at which the flow switches from sonic to subsonic mode:

$$p_{cr} = \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}}$$

Flow coefficient calculation:

- Constant

- Perry (function of p_{dn}/p_{up})



- ISO 6358 standard: defines a pneumatic orifice using two parameters:
    - critical pressure ratio *b* which localizes the boundary between subsonic and sonic flow regions
    - sonic conductance *C* which is the flow characteristic of the orifice.

EXAMPLE

Flow calculation using zeta:

TP2P00 thermal-pneumatic restriction

This submodel can be used only when Mach number of flow is lower than 0.3 (incompressible hypothesis).

$$c_q = \frac{1}{\sqrt{\zeta}}$$

EXAMPLE