FluidDissipation - A Centralised Library for Modelling of Heat Transfer and Pressure Loss

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Abstract

A new Modelica library centralising heat transfer and pressure loss calculations of energy systems called FluidDissipation will be presented. The goal of the library is to deliver a broad range of heat transfer and pressure loss correlations independent of the thermo-hydraulic framework and easy to implement (functional approach) for industrial use. Concept and numerical challenges of the library development will be described as well as first applications (Pipe flow; Environmental control system).
The FluidDissipation library is developed within the European research project Eurosyslib-D of ITEA2 funded by the Federal Ministry of Education and Research (BMBF) for 30 month started in November 2007.
Keywords: heat transfer; pressure loss; simulation; dissipation

1 Introduction

Energy conversion in any thermo-hydraulic process [1] is declined due to unwanted heat transfer (as a result of temperature difference) and pressure losses (as a result of friction) of a working fluid. Both physical phenomena increase entropy and decrease exergy of an energy system. Therefore the amount of energy of a working fluid to be transformed into mechanical work is dissipated.
These fluid dissipation effects (e.g. pressure loss of pipe network) have to be compensated by higher energy supply of other system components (e.g. delivery height of pumps). A reduction of fluid dissipation effects is a way to optimise efficiency of a thermo-hydraulic process with a corresponding minimisation of operation costs. Thus modelling fluid dissipation effects are necessary for thermo-hydraulic processes to evaluate existing energy systems and to find out optimising potentials.
Therefore the target of the FluidDissipation library is to deliver a centralised open source Modelica library including verified and validated correlations describing heat transfer and pressure losses of fluids for energy systems. Applications of the FluidDissipation library (e.g. incompressible pipe flow; Air conditioning heat exchanger with compressible moist air) will be developed with the use of the Modelica.Fluid library.

2 Library concept

The main goal of FluidDissipation as an open source library is to allow the usage of dissipation models in every thermo-hydraulic framework. Also the FluidDissipation library can be used as a multi domain base library to achieve a maximum of flexibility in implementation and further application to energy systems.
The way to obtain an overall use of the FluidDissipation library is to build up the library according to the following implementation methods:

- Library development with functional approach (literally use of function calls)
- Input and output arguments of function calls delivered by records (like geometric parameters and fluid properties)
- Implementation of continuous functions for efficient numerical simulation

3 Numerical aspects of transient fluid flow modelling

In literature there are a lot of heat transfer and pressure loss correlations within restricted boundary conditions. In order to get dissipation functions applicable

for a broad region of fluid conditions every restricted mathematical description has to be numerically improved for efficient simulation.
Numerical improvement of dissipation functions will be verified by the authors under the following aspects:

- Enlargement of heat transfer and pressure loss functions with restricted boundary conditions to a broader region via numerical interpolation with respect to physical correctness

- Use of pressure loss functions in dependence of functional output targets like:

  Mass flow rate for compressible fluid flow or

  Pressure loss for incompressible fluid flow

- Inverting of documented pressure loss functions for compressible fluid flow according to mathematical feasibility

- Linearisation of pressure loss functions for compressible fluid flow at small mass flow rates and reverse flow to avoid numerical difficulties

- Usage of inline integration [2] to improve numerical behaviour (if supported by modelling software)

4 Implementation

The concept of the FluidDissipation library allows both the interoperability with other thermo-hydraulic framework as well as an easy implementation intended for further industrial use as a result of the **functional approach (using literally function calls with records for input/output arguments)**.
The principle of the easy to use implementation for a new base pipe model is pointed out in Figure 1 to Figure 3. In Figure 1 the structure to build a new base pipe model is shown as example for this implementation. The new base pipe model consists of the following components of a chosen thermo-hydraulic library (Modelica.Fluid):

- Hydraulic and thermal connectors for data exchange

- Control volume for calculation of thermodynamic state

- Medium model (e.g. Modelica.Media) for calculation of fluid properties

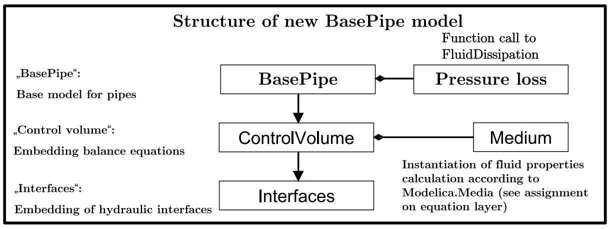

Figure 1: Implementation of a new base pipe model out of FluidDissipation functions - Structure

According to the proposed structure in Figure 1 the user needs to concentrate only on the following steps to implement the missing dissipation calculations successfully. In the following the new base pipe is modelled adiabatic and the further implementation is explained with respect to pressure losses.

1. Create a new model with inherited hydraulic and thermal connectors of chosen thermo-hydraulic library

2. Inheritance of a control volume

3. Instantiation of the medium model

4. Add corresponding records of dissipation calculation on diagramm layer of model (see Figure 2)

5. Assign record variables to input and output arguments of chosen function in equation layer of model (see Figure 3)

The diagram layer of this implementation of pressure loss with the used records is shown in Figure 2.

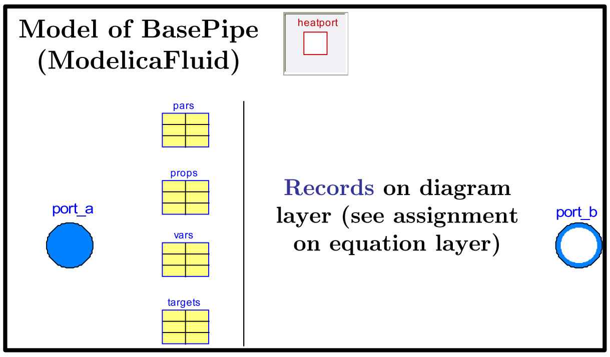

Figure 2: Implementation of a new base pipe model out of FluidDissipation functions - Diagram layer

Finally the pressure loss variables of the records in the diagram layer have to be assigned to the pressure loss function in the equation layer according to Figure 3. In this example an inline function for the mass flow rate is used. The advantage of an inline function is that either the mass flow rate or the pressure loss can be calculated in dependence of desired target variable in the current model. The medium variables are calculated for a design flow direction from the upstream control volume. Therefore the designed flow direction has to be ensured by the thermo-hydraulic process itself.

```
// Record and pressure drop function assignment
// Fluid properties
 props.vis = vis;
 props.rho = medium.d;

// Input variables (Here: pressure loss vars.dp)
vars.dp = port_a.p – port_b.p;
vars.m_flow = targets.M_FLOW;

// Output variables
targets.DP = vars.dp;
// Calculate mass flow rate out of pressure difference
targets.M_FLOW =
FluidDissipation.PressureLosses.OnePhase.General.Generic
PressureDropDensity_M_FLOW_Inline(vars.dp, props, pars);
```

Figure 3: Implementation of a new base pipe model out of FluidDissipation functions - Equation layer

5 Example application of FluidDissipation

5.1 Pressure loss in straight pipes

Straight pipes are one of the most frequently used devices in the modelling of an thermo-hydraulic process. Therefore also the development of the FluidDissipation library starts with the modelling of pressure loss in a straight pipe using the functional approach for implementation. The result of the pressure loss calculation in a straight pipe in terms of the Darcy friction factor λ_D is shown in Figure 4. The pressure loss calculation for straight pipe flow is based on the following basic correlations:

$$\Delta p = \underbrace{\zeta_{tot}}_{\text{Total pressure loss coefficient}} \cdot \frac{\rho \cdot u^2}{2} \tag{1}$$

$$\zeta_{tot} = \underbrace{\zeta_{fri}}_{\text{Frictional pressure loss}} + \underbrace{\zeta_{loc}}_{\text{Local pressure loss}} \tag{2}$$

$$\zeta_{fri} = \underbrace{\lambda_D}_{\text{Darcy friction factor}} \cdot \frac{L}{d_h} \tag{3}$$

The typical behaviour of the Darcy friction factor λ_D in a straight pipe can be divided into three flow regimes in dependence of the Reynolds number Re and relative roughness k with the following behaviour:

- Laminar regime (I) at small Reynolds number (Hagen-Poisseuille equation):

  λ_D independent of k

  Decrease of λ_D with increasing Re

- Transition regime (II) for Reynolds number in between 2300 to 4000 (Smoothing function):

  λ_D slightly dependent of k

  Increase / decrease of λ_D with increasing Re

- Turbulent regime (III) at high Reynolds number (Numerical Colebrok-White equation):

  Increasing λ_D with increasing k

  λ_D independent of Re

For very high absolute roughnesses (average height of asperities inside pipe) an additional numerical improvement has to be done for the calculation of the pressure loss. In Figure 4 the laminar regime (I) is calculated independent of the roughness. Nevertheless a numerical abortion of the solver occurs if the absolute roughness of a straigth pipe is very large. In this case the difference from the end of the laminar regime to the start of the turbulent regime is not stable even if a smoothing function is used. A numerical improvement of this problem is found in [3] with the modelling of λ_D from the Hagen-Poiseuilles calculated in dependence of the relative roughness k according to Samoilenko with an variable end of the laminar regime and corresponding Reynolds number $\mathrm{Re}^{end}_{laminar}$:

$$\mathrm{Re}^{end}_{laminar} = 754 \cdot \exp\left(\frac{0.0065}{k}\right) \tag{4}$$

The end of Hagen-Poisseuilles law in dependence of relative roughness leads to an variable upper boundary for laminar fluid flow and a better numerical stability. This numerical improvement is based on the physical behaviour shown in corresponding measurements according to [3] for commercial tubes and it is now implemented in the FluidDissipation library (e.g. bends).

5.2 Simple environmental control system

The second example demonstrates the feasibility of using heat transfer and pressure loss functions from the FluidDissipation library for system simulation. In Figure 5 a simple environmental control system of an aircraft is modelled.

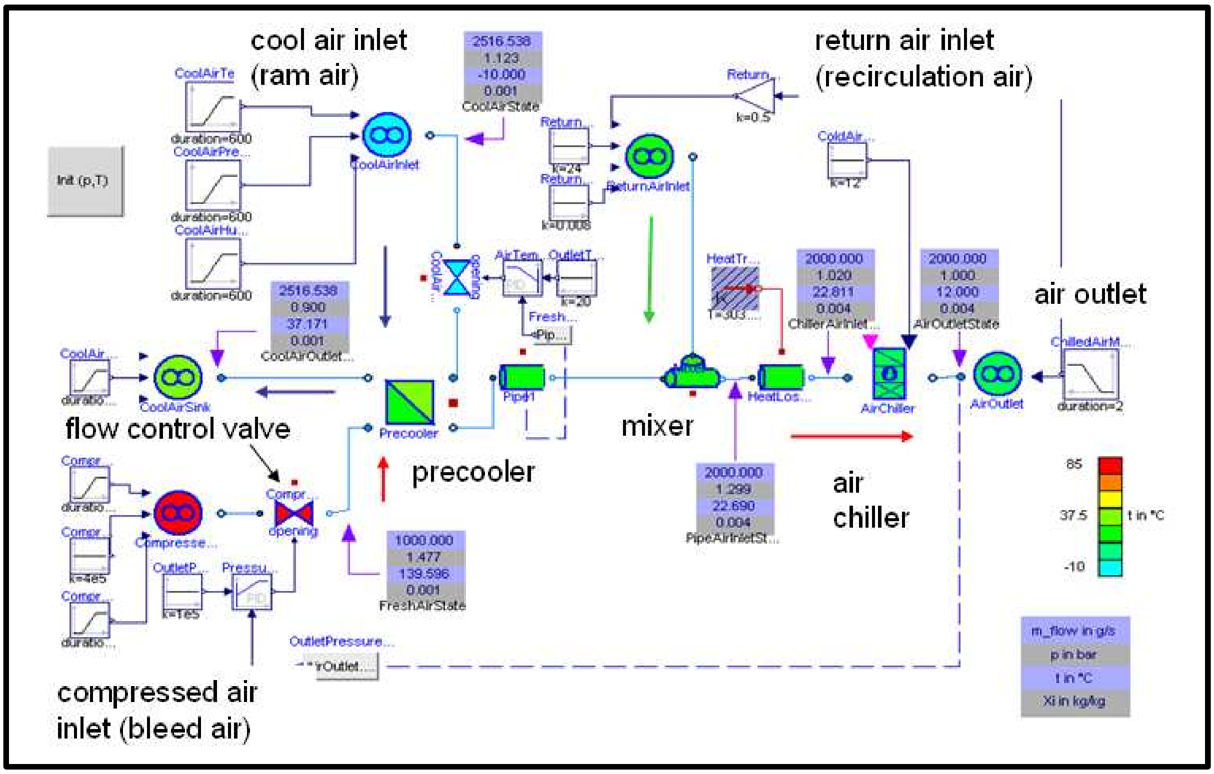

Figure 5: Model of a simple environmental control system for aircrafts

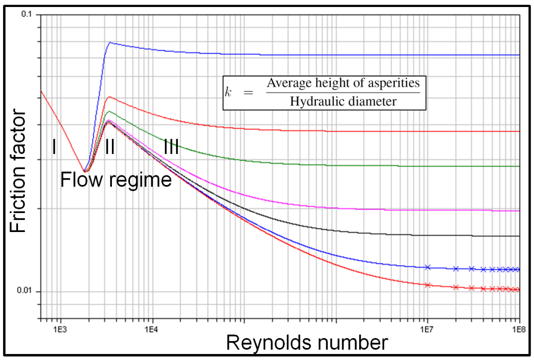

Figure 4: Darcy friction factor λ_D in dependence of Reynolds number Re with relativ roughness k as parameter

The simple example of an environmental control system for an aircraft consists of the follwing features:

- Varying ambient conditions according to flight or ground case of aircraft
- Moist air of Modelica.Media library used as medium
- Compressed fresh air (bleed air) is precooled by ambient air (ram air)
- 50% of hot cabin air is recirculated and mixed with precooled a fresh air
- Air chiller required for temperature control of inlet air for cabin
- Flow control valve for pressure control of inlet air for cabin
- **All models apply** FluidDissipation **heat transfer and pressure loss functions**

The boundary conditions for a flight test with the simple environmental control system (ECS) in Figure 5 are listed in Table 1. A flow diagram for the main part of the ECS-model is shown in Figure 6. The aim of the shown ECS is to deliver 2 kg/s of moist air with an inlet temperature of 12°C and an ambient pressure of 1 bar with the temperature and pressure control through chiller and control valves.

The most important results of a flight test under the boundary conditions listed in Table 1 are commented in the following. According to the high pressure of 2 bar of the bleed air out of a turbine from an aircraft the flow control valve has to adjust the pressure loss to achieve the desired inlet pressure of 1 bar to the cabin in the ground case. The pressure loss function inside the flow control valve adjusts the needed pressure loss via opening. In Figure 7 the transient pressure of compressed bleed air is shown from the inlet and achieves ambient condition after the chiller.

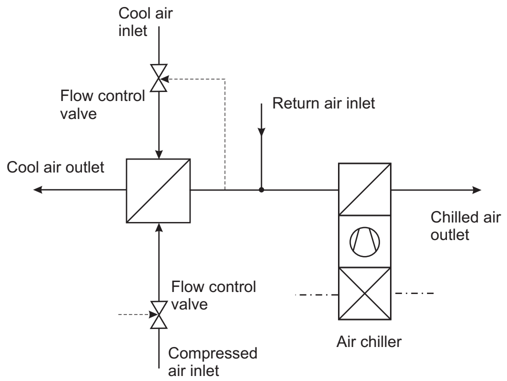

Figure 6: Example air conditioning system layout

Table 1: Boundary conditions for simulation

Compressed air inlet		
p	bar	2.0
ϑ	°C	140
Xi	kg/kg	0.012 … 0.001
Cool air inlet		
p	bar	1.5 … 1.2
ϑ	°C	30 … -10
Xi	kg/kg	0.012 … 0.001
Cool air outlet		
p	bar	1.0 … 0.5
Return air inlet		
$\dot{m}$	kg/s	1.0
ϑ	°C	24
Xi	kg/kg	0.008
Chilled air outlet		
$\dot{m}$	kg/s	2.0

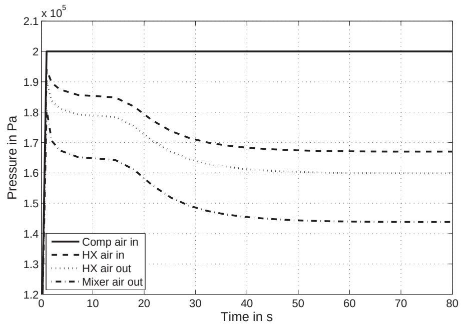

Figure 7: Transient pressures of compressed air from inlet to mixer

The pressure control for the cabin is realised due to the relative opening of the flow control valve and corresponding pressure loss according to Figure 8. The total pressure loss coefficient ζ_{tot} is increasing as result of a decreasing opening of the flow control valve (higher local pressure losses ζ_{loc}).

Also the effect of heat transfer losses to the environment have been considered in a straight pipe in between the mixer and chiller unit with a konstant heat transfer coefficient. Finally in Figure 5.3 the inlet temperature of moist air to the cabin as main task of the environmental control system is simulated. It is shown that the existing environmental control system of the aircraft under ground conditions is not able to fulfill the default inlet temperature of 12°C to the cabin. To reach the set temperature for the ground case the cooling capacity of the chiller has to be raised. However during the flight case the ram air reaches the set value of 12°C for inlet temperature due to the decreasing ambient pressure and temperature leading to higher precooling. Therefore all models applying pressure loss calculation (e.g. Flow control valve, precooler

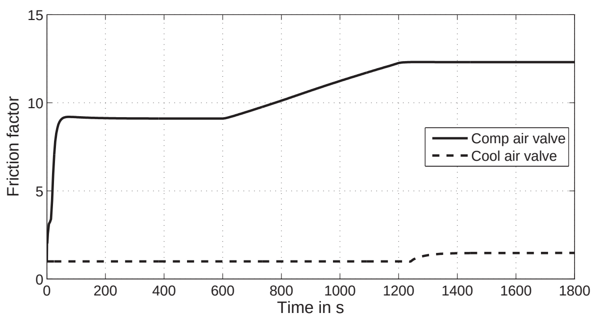

Figure 8: Friction factors of valves due to decrease of relative opening

,straight pipe, etc.) fulfill the requirements of being used in large thermo-hydraulic systems like environmental control system.

5.3 Summary

The concept of the a new Modelica library called FluidDissipation has been presented. FluidDissipation is developed in the European research project

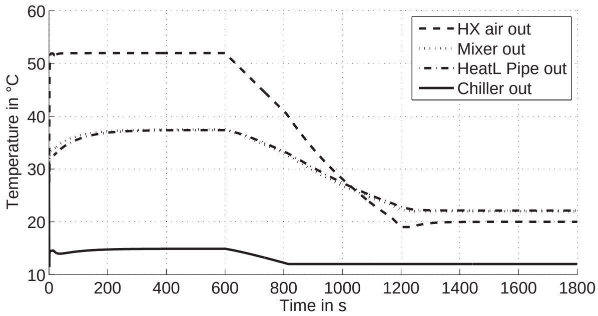

Figure 9: Transient temperatures of compressed air from HX outlet to chiller outlet

Eurosyslib-D and will be a free library for calculation of heat transfer and pressure losses of energy systems. First examples like fluid flow in straight pipes and a simple environmental control system have shown possible applications for energy systems. Further tasks are the enhancement of more heat transfer and pressure loss calculations of energy devices. For the verification and validation measurement results have to be supplied.

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