Community Updates to the DLR ThermoFluid Stream Library

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Abstract

Since its inception in 2021, the user base of the DLR ThermoFluid Stream Library has steadily grown. This growth was accompanied by improved or refined models, new additions such as models for static head pressure and also new examples, especially for teaching. This paper summarizes these updates for the reader and reports on the recent developments.

Keywords: Thermal Modeling, Pipes, Pumps, Heat Exchangers, Static Head, Media modeling

1 Introduction

Since winning the Modelica Library Award in 2021, the DLR ThermoFluid Stream (Zimmer, Meißner, and Weber 2022) Library steadily grew in popularity with users all around the world.

To further encourage both usage but also contributions, we staged the first ThermoFluid Stream (TFS) community event, which took place as a pure online event on June 19, 2024.

The preparations for this event led to many notable contributions for this library which have widened its application field but also have increased the fidelity of its components. This paper reports on these contributions.

1.1 What is special about the DLR ThermoFluid Library?

The ThermoFluid Stream Library distinguishes itself from other approaches by its robust modeling concept (Zimmer 2020) that avoids the formulation of large non-linear equation systems that span across components. Also it supports initialization at zero mass-flow which makes the library relatively easy to use even for complex architectures.

1.2 Overview

Figure 1 providers a quick overview of the library for readers that are unfamiliar with its content. We will highlight certain elements and sections throughout this paper to provide guidance where to find the additions.

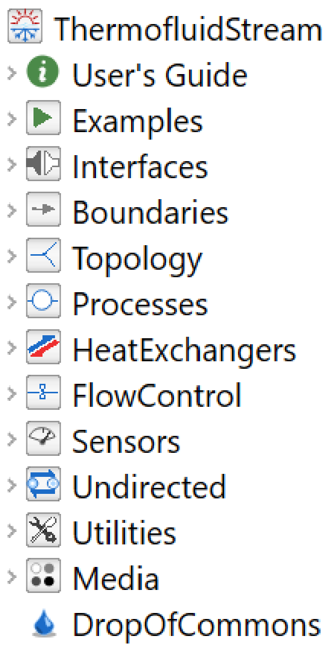

Figure 1. Overview of the TFS library

2 New Concepts and Interfaces

2.1 Static Head Pressure

Pressure increase due to gravitational acceleration had been largely ignored by the prior versions of the Thermofluid Stream Library. A simple tank model with its height vector defined as being parallel to the gravitational vector was the only exception.

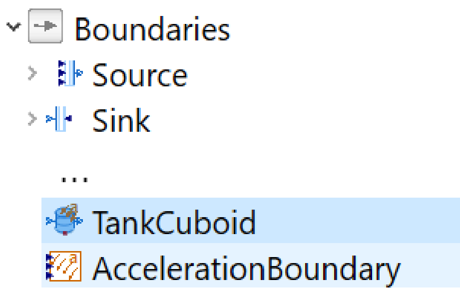

Figure 2. cuboid tanks and global acceleration model

The new update now includes models that aim to provide a more general solution than just constant gravitational acceleration. Instead the thermofluid system can even be regarded as part of a moving object with a globally defined vector for acceleration that can change over time. This is for instance relevant for applications in aircraft or spacecraft.

To this end, a second inner/outer model is provided to specify the acceleration vector. There exists a static head model for pipes that computes the static head pressure based on the coordinates of its starting and end point. Furthermore, there is an elaborate model of cuboid tanks that approximates the liquid surface based on the direction of the acceleration vector and the geometry. Knowing this, enables the computation of the static head pressure for its various inlets and outlets.

This solution is also provided for bi-directional components.

2.2 Interface to TIL Media

The usage of sophisticated media models plays an important role in the modeling of thermal architectures. Robust media models with high computational performance are inevitably needed, especially for phase changing refrigerants that become more important in future thermal management systems. As such media models are provided in the TILMedia Suite (*TIL Media Suite* 2024) developed by TLK Thermo GmbH, an interface to enable their usage within the TFS was developed (TILMediaWrapper).

The current state of the wrapper is a Dymola specific implementation and only supports vapor-liquid equilibrium (VLE) fluids (phase changing media). In general, the interface follows the structure of the TILMedia Suite itself. The basic idea is to adjust the VLE-Fluid model of the TILMedia Suite with pressure, enthalpy and mass fraction as independent variables to match the TFS media interface. In the corresponding package, the functions of partialTwoPhaseMedium are redeclared and the thermodynamic properties are calculated with the functions from the TILMedia Suite.

For each media model that needs to be interfaced, an according substance record has to be defined and then custom media models can easily be added. Also media models inherited from other libraries as Refprop, Coolprop or the VDI Heat Atlas are available and can be added.

Keep in mind that the package only provides the functionality of an interface to the TILMedia Suite and does not include the media models itself! For usage of the media models, a license of the TILMedia Suite is necessary.

3 Improved Components

3.1 New Pipe and Fitting Models

For this update, piping models for pipes and fittings respectively like curved bend, edged bend, sudden contraction and expansion, as well as edged orifice have been developed utilizing the provided pressure loss functions in `Modelica.Fluid.Dissipation.PressureLoss`. The components calculate either the pressure change from inlet to outlet Δp depending on the mass flow rate $\dot{m}$ or the mass flow rate $\dot{m}$ depending on the pressure change Δp along the component using medium properties and geometry. The advantage of re-using standard library components for TFS is in their well known and well validated background.

Additionally, several new models for diffuser, Y-splitter and Y-junction flow have been implemented, based on Idel'chik and using the TFS framework. All novel models are verified against literature or partially validated against CFD flow simulations.

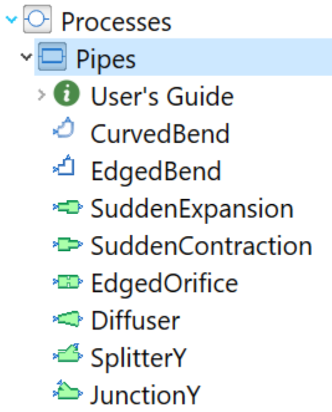

Figure 3. new pipe models

The curved and edged bend models are adaptions of the respective models from `Modelica.Fluid.Fittings.Bends` to enable their usage within the TFS environment. Both bends consider wall friction as well as geometry induced pressure losses. The flow path of the edged bend is assumed to be five perimeters up- and downstream of the edge. For incompressible application it is recommended using default setting `assumeConstantMaterialProperties = true`, while neglecting this choice is beneficial for compressible calculations e.g. $Ma > 0.3$.

The models for sudden contraction and expansion of a circular pipe are utilizing the sudden-change pressure loss function from `Modelica.Fluid.Dissipation.Orifice` and extend the novel partial model `SISOFlow_nonConstArea`, which is based on the Bernoulli equation. The models for sudden contraction and expansion respectively are basically identical and differ only in their icons as well as flow direction.

The edged orifice model is equivalent to `Modelica.Fluid.Dissipation.Orifices.ThickEdgedOrifice` and therefore it shares the same pressure loss function. The difference to Modelica Standard Library (MSL) is in the definition of the Darcy friction factor λ_{fric} as parameter, which enables a calibration of the model.

The diffuser model is a model of a conical diffuser based on equations from Idel'chik (1966). Here, the local coefficient of flow resistance consists of two components, one for expansion and the other for friction. k_1 characterizes the state of the boundary layer, here a uniform velocity profile is assumed ($k_1 = 1$).

$$\zeta_{dif} = k_1 \cdot \zeta_{exp} + \zeta_{fr} \tag{1}$$

For diffuser opening angles $\alpha \leq 40°$ the flow resistance is calculated as

$$\zeta_{exp,1} = k_2 \cdot \tan\frac{\alpha}{2} \cdot \sqrt[4]{\tan\frac{\alpha}{2}} \cdot (1 - \frac{A_0}{A_1})^2 \tag{2}$$

with k_2 for the cross sectional shape of the diffuser (circular: $k_2 = 3.2$) and an inlet to outlet area-ratio A_0/A_1. For $\alpha > 60°$ a polynomial function is used

$$\zeta_{exp,2} = p_1 \cdot \alpha^2 + p_2 \cdot \alpha + p_3 \tag{3}$$

with the coefficients $p_{1,2,3} = f(A_0/A_1)$ which are manually fit to the diagrams in Idel'chik (1966). The transition region $40° \leq \alpha \leq 60°$ is approximated by a cubic-hermite spline (C-Spline). The wall friction is determined by

$$\zeta_{fric} = \frac{1.5 \cdot \lambda}{8 \cdot \sin\frac{\alpha}{2}} \cdot \left(1 - \frac{A_0}{A_1}\right)^2 \tag{4}$$

Equation 4 is an adaption of Idel'chik (1966), since the original equation leads to non-physical pressure losses for small angles and it is based on the work of Mfon et al. (2019).

The model for flow splitter assumes a diverging y-pipe of branching angles $15° \leq \alpha \leq 90°$ with circular cross section. For implementation of the basic flow equations a partial model similar to `ThermofluidStream.Topology.SplitterN` is used, but limited to 2 outlets and extended by dynamic pressure. Two geometry types are distinguished

I) straight pipe with attached pipe branch ($A_b + A_s > Ac$ and $A_c = A_s$)

II) straight pipe splitting in two smaller branches, whereby the inlet area equals the overall outlet are ($A_b + A_s = A_c$). Depending on the users choice the corresponding pressure loss function based on Idel'chik (1966) is used. Each function calculates both flow resistances, one in the straight channel ζ_s and the other in the pipe branch ζ_b with respect to the velocity in the common channel v_c and outputs the respective pressure loss Δp. The model is limited with respect to the flow design direction.

The junction model is the flow-reversed equivalent to the splitter model. It describes the same geometry specifications and differentiation as the y-shaped splitter. Since mixing fluid streams is far more complex than separating, a specialized partial model is required. This model uses an adaption of `ThermofluidStream.Topology.JunctionN`, calculating the mixing properties for two fluid streams of

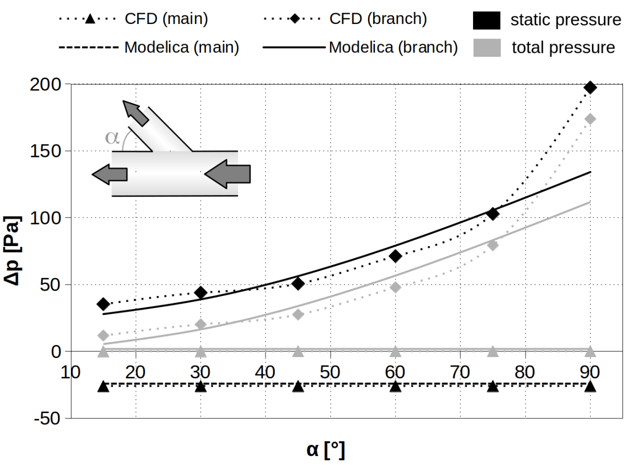

Figure 4. Validation of the Modelica splitter flow model against CFD

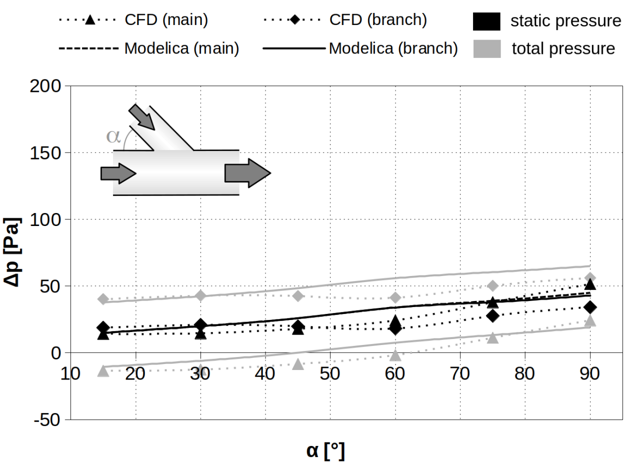

Figure 5. Validation of the Modelica junction flow model against CFD

the same medium, while taking the conservation of kinetic energy into account. The extending model calls the pressure loss functions based on (Idel'chik 1966), depending on the geometry type.

As mentioned above, some models have been verified against CFD calculations. Those models representing a re-use of the Modelica standard library did not require a validation, only a verification. The models for splitter and junction flow are new, and therefore the were partially validated. The validation has been performed against ANSYS CFX, whereby water as incompressible fluid was taken. In CFD the walls have been treated as free slip walls, because the 1-D models also don't consider wall friction losses. The calculations were performed against a range of splitter/junction angles. Figure 4 and Figure 5 show the result of the validation for both, the static (black) as well as the total (grey) pressure change. Considering the complexity of a 3D flow and the generic usage of such a 1D model, both cases show a good agreement and are therefore useful for pipe flow simulations.

3.2 New Pump Models

Models for simple pumps and centrifugal pumps have been developed. Following the TFS approach all models avoid non-linear equation systems and work for zero mass flow rate $\dot{m}$ and/or zero angular velocity ω.

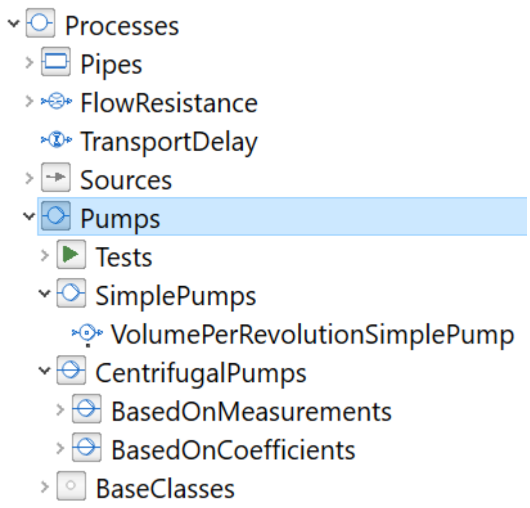

Figure 6. new pump models

A simple pump uses a constant efficiency η and ensures either

1) a given pressure difference Δp or
2) a given outlet pressure p_{out}, comparable to a an electrical voltage source `Modelica.Electrical.Analog.Sources.SignalVoltage`, or
3) a given mass flow rate $\dot{m}$ or
4) a given volume flow rate $\dot{V}$, comparable to an electrical current source `Modelica.Electrical.Analog.Sources.SignalCurrent`.

The set-point may be either a constant parameter or a time varying signal using real input connector.

In addition, there is a simple piston pump model with a fixed volume flow per revolution using a mechanical flange connector comparable to `Modelica.Electrical.Analog.Basic.RotationalEMF`.

Centrifugal pumps use similarity laws for head $h \sim \omega^2$, volume flow rate $\dot{V} \sim \omega$ and power $P \sim \rho\omega^3$ of angular velocity ω and density ρ and quadratic polynomials for head h and power P as a function of volume flow rate $\dot{V}$. The 6 coefficients can be determined by approximation of measurements at reference angular velocity ω_{ref} of head h_i and power P_i at volume flow rates $\dot{V}_i$. In addition, a method was developed to scale existing pumps or to estimate a reasonable centrifugal pump requiring only minimal user knowledge. The TFS provides pump data (measurements and coefficients suitable for scaling) of 19 centrifugal pumps using records. Thereby the user may add a new pump simply by defining a new record.

3.3 New 2-Phase Heat Exchanger Models

When condensation or evaporation happens in heat exchangers, the heat exchange rates change dramatically. Therefore, models become very inaccurate if they describe heat exchangers by constant coefficients.

However in cooling processes, phase changes are occur regurlarly. We therefore developed models for heat exchangers which calculate the heat exchange rates based on the physical processes.

Three types of processes have been considered:

- film condensation of a 2-phase fluid
- evaporation of a 2-phase fluid
- condensation of water vapor in liquid air

With these processes the cooling of humid air as well as cooling by a vapor cycle can be remarkably precisely described. Besides the physical constants of the media only geometric data of the heat exchanger are required.

The description of the physical processes is taken from the text book of (Baehr and Stephan 2010).

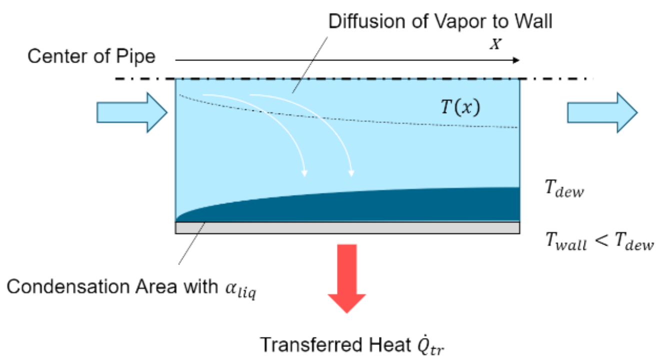

Figure 7. Illustration of the condensation of vapour at the walls of a pipe

4 Tool Support

4.1 Compatibility

We check the compatiblity to differemt Modelica compilers, most notably OpenModelica (Fritzson 2018). These cross checks ensure that the library is available for a wide range of users for free.

4.2 Improved Performacce

A notable improvement regarding the simulation performance has been made in Dymola that benefits the simulation of 2-phase systems. Thanks to this implementation, the examples of vapour cycle and heat pump now run three times faster. The improvements become available with version 2025x.

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5 Application

5.1 Application in Teaching

At HTWG Konstanz in Germany, the TFS is used for teaching of system design and simulation focusing on renewable energy systems. The TFS library provides a wide-ranging set of important components, media as well as examples suitable for teaching purpose. Its simple application and robustness enables students to achieve rapid progress in modeling and simulation. Besides the demonstration in lecture, HTWG Konstanz places great value on practical training. In practice lessons and projects the students are empowered to model and simulate complex thermo-fluid systems using TFS as well as developing on models using the TFS-framework.

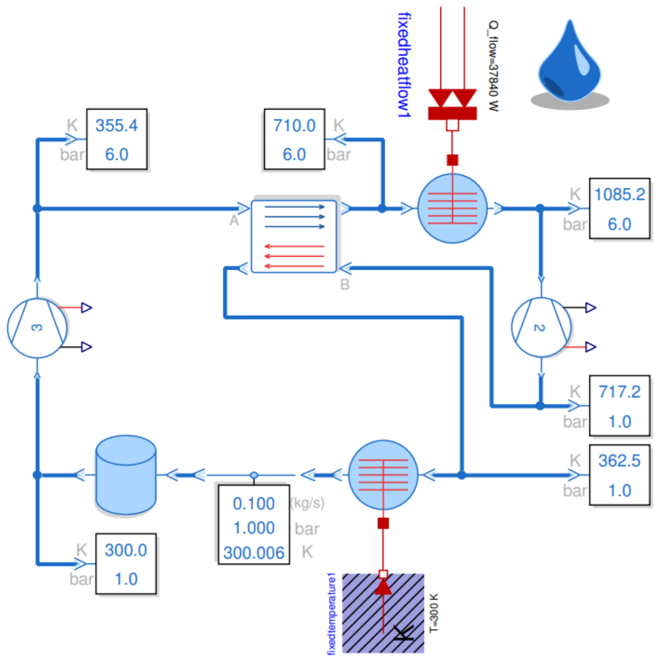

Figure 8. Example of an Ericsson cycle taken from (Junglas 2023)

At PHWT in Vechta/Diepholz in Germany the study of classic thermodynamic cycles is part of the curriculum. Using only literature, this is often very dry and provides little excitement for the students. Using the TFS enabled us to create models of classic cycles such as the Ericsson cycle and the Clausius-Rankine cycle (Junglas 2023). While setting up these simulation models is still substantial work, it can be made available to the students for free using OpenModelica.

5.2 Usage for Aircraft Systems

In the European project Thema4HERA which is part of the Clean Aviation initiative, the aircraft industry, most notably the system suppliers research on new solutions for aircraft thermal management. Here the DLR ThermoFluid Stream Library is used as basis for a Digital Twin. The corresponding model focuses on the main environmental control system including the different cabin sections and is able to perform full mission evaluation.

6 Outlook

We were very glad seeing the DLR ThermoFluid Stream library grow so much in popularity. First, this is a validation of our effort and clearly reveals how much users appreciate robust components and a robust modeling methodology. Second, it encourages us to go on with the development of the library and improve its quality. Finally, we want invite the Modelica community to contribute to this library. A healthy community of users and developers is ultimately best driver for success.

Acknowledgements

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