Modelling of complex thermal energy supply systems based on the Modelica-Library *FluidFlow*

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Abstract

The new Modelica library *FluidFlow* is being developed for the thermo-hydraulic simulation of complex energy supply systems. This library includes standard hydraulic model classes and specialized components for HVAC-systems and solar thermal systems. Most of these Modelica classes are modelled with equations of the 1D-transient energy transport. The validation of the library takes place both by measuring values from test stations and by comparing with detailed CFD models. A first complex use case of the library represents the simulations-based design of a complex thermal energy supply system of a residential area, as a part of a newly built city in Iran.

Keywords: thermo-hydraulic simulation; validation with CFD; modelling of complex energy supply systems

1 Introduction

In the last years, different Modelica-libraries for the hydraulic and thermo-hydraulic simulation were developed [1, 2]. From our point of view, these libraries are not well suited for the modelling of very complex thermal energy supply systems, because their structure are either too complex within their single components or do not include a lot of the required specialized models. For this reason, the authors decided to develop a new Modelica-library for thermo-hydraulic network simulation, which is called *FluidFlow* [3].

2 Modelica library *FluidFlow*

The present main application field of the *FluidFlow*-library is the modelling of solar thermal systems, HVAC (Heating, Ventilation and Air-Conditioning)-systems and district heating/cooling systems.

2.1 Library structure

The *FluidFlow*-library comprises thermo-hydraulic models and purely hydraulic models. The skeletal structure of the library consists of a set of “ready-to-use” standard hydraulic models, such as pipes, elbows, distributors and pumps. These models are built on variably specialized “partial”-Modelica classes - e.g. for pressure loss calculations, heat transport, model interfaces design - by the intensive use of the object-oriented modelling technique.
In addition to the standard components, the library includes more specialized models from several domains (compare with Figure 1), such as solar thermal technology (collector models), thermal storage technology (storage models) or energy transformation technologies (e.g. models of heat exchangers, absorption chillers and cogeneration plants).

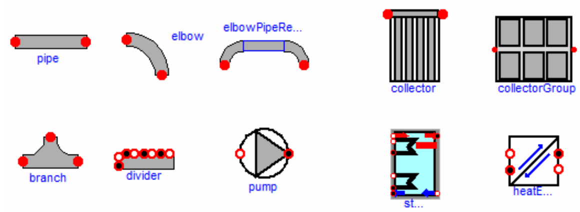

Figure 1 Standard models (left) and specialized models (right) of the thermal-hydraulic library FluidFlow

2.2 Physical models

All the hydraulic models of the *FluidFlow*-library are based on a stationary pressure loss-calculation, which depends on the component type, its individual parameters and the present flow conditions. In addition, the thermo-hydraulic component models have transient thermal models both for the 1D-convective energy transport in the flow direction and for the heat transfer to the environment. Some of the models such as the thermal storage also have models for the diffuse and turbulent heat transport within in the fluid. The *FluidFlow*-library also supports reverse flow. So the flow directions within the modelled systems only depend on the external boundary conditions of the corresponding thermo-hydraulic network and the induced pressure values or mass flows of the net-integrated pumps. All the models of the *FluidFlow*-library can be used with or without the *Modelica.Media*-library.

2.3 Validation

The validation of the single thermo-hydraulic components and system models takes place in two different ways. The first method represents the traditional validation with measurement values, used from thermo-hydraulic test stations from the Technical University of Berlin [4]. At the moment the validation of the component models such as thermal water storages with and without internal heat exchangers, external plate heat exchangers, pipes, solar thermal collectors and also of the system model of a solar thermal plant is taking place.
The second method consists of the comparison of the simplified 1D-Modelica models with detailed 3D-models, which are based on Computational Fluid Dynamics (CFD) calculations [5].

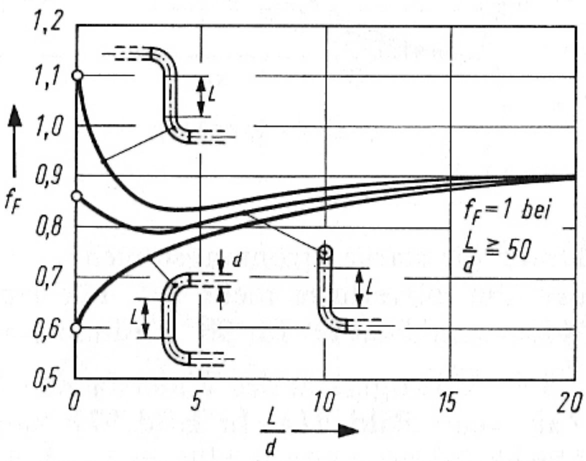

Figure 2 Reduction factor f_F for the total pressure loss for the configuration "elbow – pipe –elbow" in dependency of the length L of the intermediate pipe [6]

One result of this approach is the improvement of the accuracy of the thermo-hydraulic "group-behaviour" of several Modelica component models, which are connected to a system model.
Therefore, we analysed in a first step the pressure loss of a small hydraulic system with three serial connected components – an elbow, a straight pipe and a second elbow with the geometry in Figure 2 down on the left side: if the length *L* of the intermediate pipe is relatively short in comparison to its diameter *d*, then the impact of pressure loss from both elbows on the pressure loss of the pipe is considerable. In this case, the total pressure loss of the three components is smaller than the sum of the single pressure losses of each component (expressed with the reduction factor f_F), because the equations used for the pressure loss calculation in the Modelica models assume for each of the three components an undisturbed flow profile at the inlet and outlet, which here does not exist:

$$\Delta p_{total} = f_F \cdot \left(\Delta p_{elbow1} + \Delta p_{pipe} + \Delta p_{elbow2} \right) \quad (1)$$

But in the case of a relative long intermediate-pipe (values $L/d \geq 50$), the sum of the single pressure losses approximates the total pressure loss of the small hydraulic system (compare with Figure 2) and f_F becomes to 1.
First, we modelled the described hydraulic system with the CFD-tool ANSYS CFX 11.

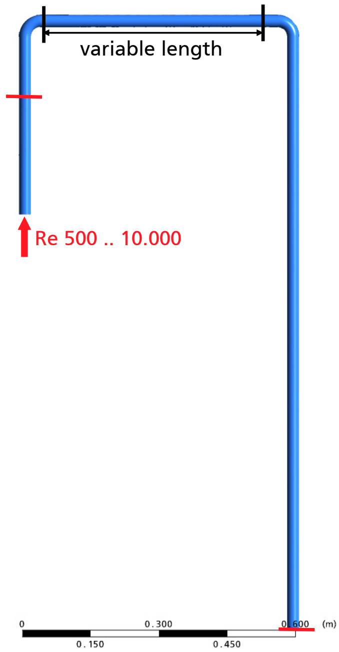

Figure 3 3D-CFD-model of two 90° elbows with an intermediate pipe with variable length

In the CFD-model we add two pipes for an additional inlet and outlet stretch, to have an undisturbed flow profile at the red marked cross section on the left side and only a small influence from the second elbow on flow profile at the red marked outlet cross section on the right side (compare with Figure 3). Then we calculated the total pressure loss between both red marked cross sections. We did also a further CFD-calculation for a straight pipe with the same *L/d*-value. The difference between the total pressure losses of both calculations are induced only by the elbows forcing a flow direction change. We did these calculations for Reynolds-numbers between 500 up to 10,000 and *L/d*-values between 0 up two 50 and deduced a correction function $f_F=f(L/d)$ (compare with Figure 4).

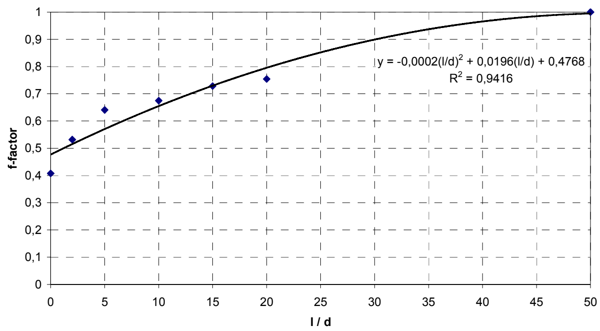

Figure 4 CFD-deduced correction function for the component group "elbow – pipe – elbow" (mean values for Reynolds numbers from 500 to 10,000)

Figure 5, the drawing in the left, shows a "conventional" Modelica configuration of a hydraulic loop, based on single independent components. Figure 5, the drawing in the right, demonstrates the same loop with a merged component, which takes into account the strong hydraulic dependencies between two elbows due to a relatively short intermediate pipe with the help of the correction function.

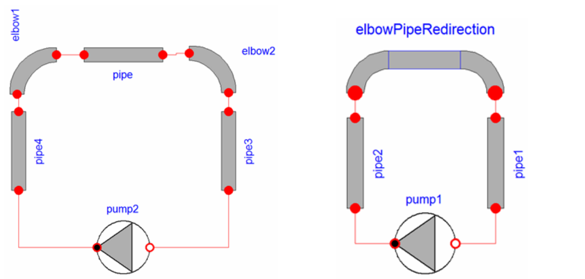

Figure 5 Configuration of a hydraulic loop with single components (left) and a "compound-component" (right)

Figure 6 shows the calculated pressure loss of the hydraulic loop (Reynolds number = 5,000), based on single Modelica component models and with a compound-component, where the calculated pressure loss is modified by the use of the new correction function. For small values of *L/d* the "real" pressure loss lays 5 up to 15 percent lower than a pressure loss calculation without a correction function.

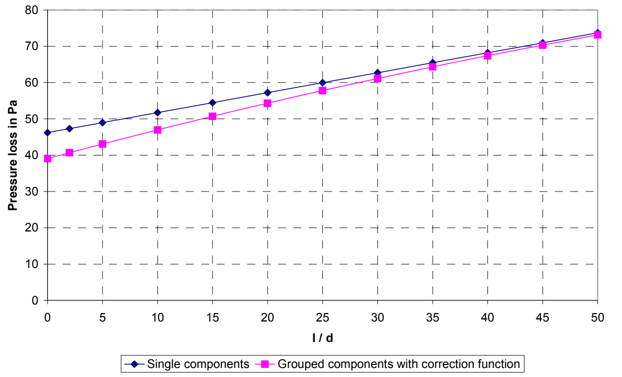

Figure 6 Calculated pressure loss of the hydraulic loop with single components and with a compound-component with the correction function (Reynolds number = 5,000)

3 Use case: modelling of a thermal energy supply system of a district

The newly developed *FluidFlow*-library is being used and evaluated within the research project "Young Cities - Developing Energy-Efficient Urban Fabric in the Tehran-Karaj Region" [7].

Figure 7 New Town Hashtgerd (Iran) and urban planning model of the 35 ha pilot area for 8,000 inhabitants

Here, the Modelica library is used for the simulation-based design of complex (thermal) energy supply systems for a 35 ha residential district as a part of the newly built Iranian city Hashtgerd with 2,000 accommodation units for 8,000 inhabitants.

For the determination of the approximate size and the boundary conditions for a suitable energy supply system, a first estimation of the heat and cold demand for the 35 ha residential area, based on an early design of the building typologies from the architects and urban planners was performed.

Using the geometry, construction and building materials of a typical three-storey row house of 33 m depth and 7.5 m width, the energy demand for a single building was estimated by using the program CASANOVA [8] with climate data for Karaij. Because energy efficiency is one of the main targets of the "Young Cities"-project, the U-values for the walls, roofs, basement ceilings and windows were chosen to obtain a total thermal energy demand for heating and cooling of 50 percent relative to the limits of the "Code 19"-building Iranian energy standard [9]. The energy demand of the whole 35 ha district was projected as the product of the specific energy demand of the single building and the planned total living area of the district (compare with Figure 8).

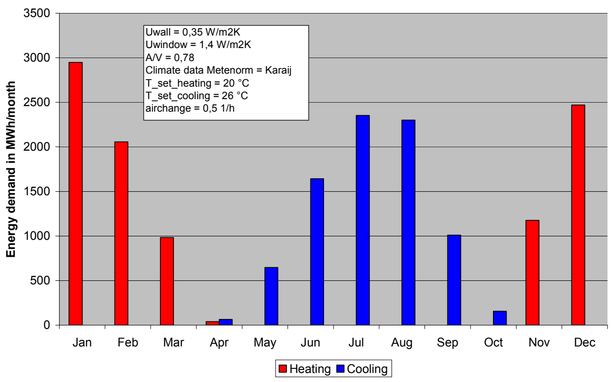

Figure 8 Projected monthly heating and cooling demand for the 35 ha district (50 percent of the Code 19)

To estimate the energy demand, a nominal room temperature of 20°C in heating periods and of 26°C in cooling periods was presumed, in addition to a ventilation rate of 0.5 h^{-1}. During cooling periods sunscreens were introduced, leading to a 50 percent shadowing of the windows. Based on these assumptions the heating period reaches from November to March and the cooling period from May to October. In April the climate in Karaij is balanced well enough that neither cooling nor heating is necessary.

In consideration of these boundary conditions different concepts of the thermal energy supply are being developed. These can have central, semi-central or de-central characteristics. Figure 9 shows an option with central heat supply and decentralised cooling production, based on solar energy. Therefore, this version contains one central thermal distribution network and many separate decentralised absorption chillers and solar thermal collector fields. Because the local solar irradiation of Hashtgerd is approximately 1,900 kWh/m^{2}a, active solar cooling can be attractive besides passive cooling for building climatisation with a minimum of primary energy.

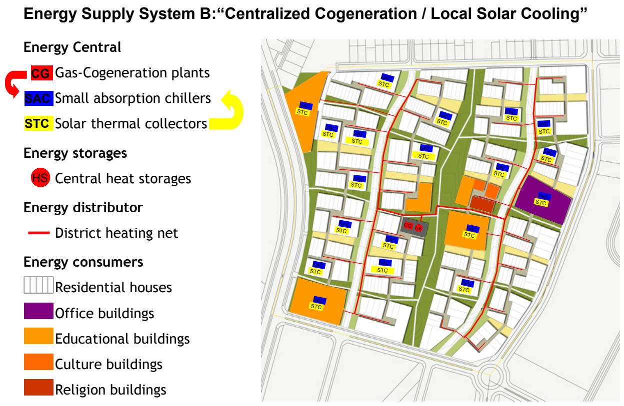

Figure 9 Energy concept of a thermal energy supply system for a 35 ha district in Hashtgerd (Iran)

The application of the *FluidFlow*-library shall be demonstrated by the modelling of the energy system of Figure 9. In this case, only the left part of the energy system is represented in the system model, illustrated in Figure 10.

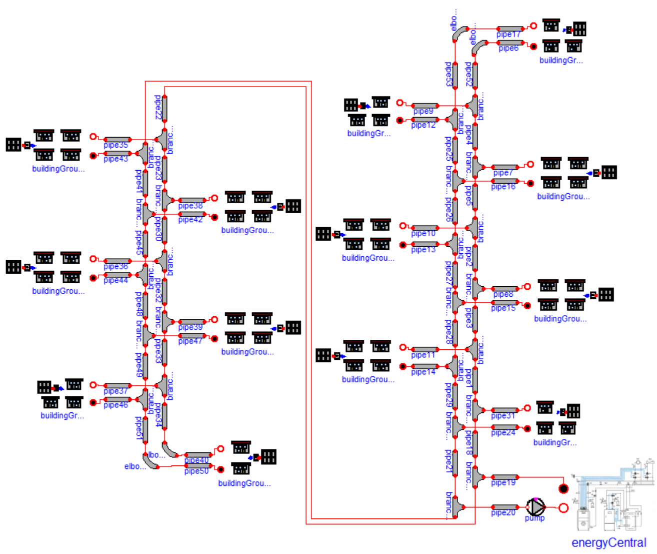

Figure 10 System model of the left part of the thermal energy supply system for the 35 ha district (variant centralised cogeneration/local solar cooling)

The modelled subsystems are the energy central (co-generation plant with a peak boiler and a thermal storage), the district heating net for the heating and warm-water demand and the thermal consumers, modelled as groups of simplified thermal building models, including the decentralised solar cooling systems (compare Figure 10, 11 and 12). The number of equations of the (non symbolic-reduced) system model of the energy supply system amounts to more than 30,000.

Figure 11 shows a sub-model for a building group with two building models. Here, each building model represents a bar of row houses, which are supplied with hot water from the central energy station and with cold water from the decentralised solar cooling system. The back-up thermal energy for the solar cooling system is also provided by the centralized thermal energy supply. Each of the building models has two controllers to adapt the mass flow through the heat exchangers for the respective heat or cooling demand at the moment. The modelling approach for the building models is strongly simplified to reduce the number of equations: The building model takes into account one thermal zone, only separates outer and inner positioned thermal masses and solely calculates the passive solar gains and shading devices for four main orientations [10].

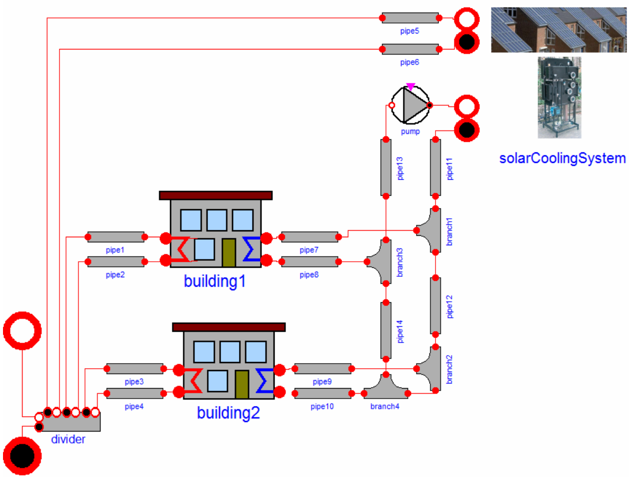

Figure 11 Sub-model of a building group with a decentralised solar cooling system

Figure 12 illustrated the model structure for the decentralised solar cooling system. The most important component of this sub-system model is a small-scale absorption chiller, which can provide some residential houses with cooling energy [11]. At this, the main part of its thermal operating power comes from the thermal storage, which is loaded by the solar collector field. If the absorption chiller needs additional thermal energy from the back-up system, it is transferred by a plate heat exchanger.

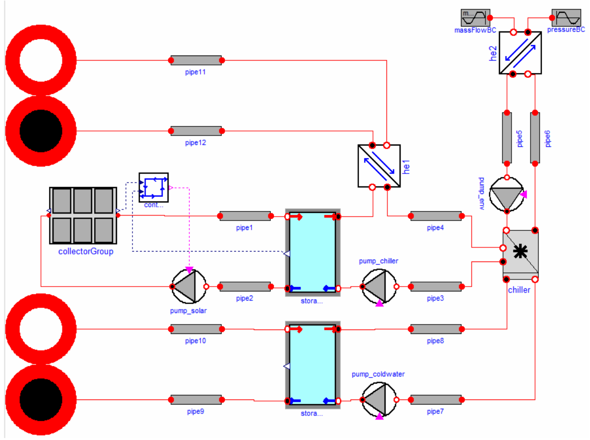

Figure 12 Sub-model of the solar cooling system with an absorption chiller

The thermal waste energy is delivered to the environment by a separate thermal circulation. The produced cold water is stored in further thermal storages, from where the building is provided with cooling energy.

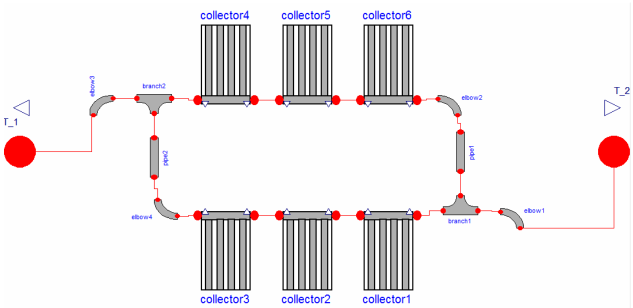

Figure 13 Sub-model of a collector field

Figure 13 shows the sub-model for a collector field. Six solar thermal collectors are serial-parallel connected with the use of the basic components of the *FluidFlow*-library. All the collector fields are integrated in the envelopes of the air-conditioned buildings.

4 Conclusion

The newly developed Modelica library *FluidFlow* is being used the first time to model a very complex thermal energy system. Here, the great challenge consists in an enough detailed modelling for all parts of the system model and a simultaneous limited number of model equations, which enables yearly simulation analysis. So, the next steps of our research activities will aim on the reduction of the complexity of the system model without a too large loss of model accuracy. For this purpose, energy system models with a different level of simplification shall be developed with the help of the *FluidFlow*-library and compared in terms of their accuracy and numerical effort.

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