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Robust Modeling of Volumes for Dynamic Simulations of Thermo-Fluid Stream Networks ⋆

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Abstract: Modeling of complex thermo-fluid systems often leads to either many states or large non-linear systems of equations, which are both undesirable especially for real-time applications. Both of these issues can be solved by our algebraic stream-dominated approach to build hard real-time capable simulations. In this approach volume elements play a central role as boundaries and loop-breakers for fluid streams.

In this paper, we first derive a lumped state standard volume model from first principle and then several specialized volumes for different applications. We regularize the models to perform robustly, even in degenerated operating conditions that might appear in dynamic simulations. While doing so, we show all approximations and assumptions used to arrive at the final models. Finally, we present some application examples showcasing the use of the different volumes for dynamic simulations. Alongside the models developed in this paper these examples are part of our open-source Modelica library and their implementation is therefore available.

Keywords: robust modeling, first-principle modeling, real-time, thermo-fluid systems, dynamic simulation

1. INTRODUCTION

Robust dynamic simulation of large (system-level) thermo-fluid networks is a challenging problem, as any lumping of states leads to non-linear equations, and in consequence often to large non-linear systems of equations. Typical approaches use either a finite volume approach (e.g. Moukalled et al. (2016); Franke (2009)) or an algebraic stream approach like most elements of the Modelica Standard Fluid library (Franke (2009)). While the former avoids the implicit computation of the non-linear systems, it relies on many states. The result is a very large ordinary differential equation and real-time capability is not feasible for system-level simulations. The latter avoids all or most states by defining boundaries for a stream of fluid, as well as the non-linear equations for the components manipulating the thermodynamic state of the fluid along the stream. The result is an algebraic system with often large non-linear systems of equations that in general is hard to solve robustly.

For many applications, especially ones that require hard real-time capability like onboard fault diagnosis or model predictive control, the approaches above are either too slow (finite volumes) or the non-linear solver is not robust enough (algebraic stream approach). For this reason, a stream-dominated differential-algebraic approach was developed at DLR (Zimmer et al. (2018)) and recently open-sourced a Modelica implementation on GitHub as DLR ThermofluidStream Library (TFS) (Zimmer et al. (2021)). The library uses the Modelica Standard Media Library (Casella et al. (2006)) and hence has a wide range of media available by default.

The stream-dominated differential-algebraic approach combines thermodynamic streams with pressure-mass-flow dynamics and uses the concepts of inertial and steady-state pressure to solve the non-linear equations explicitly from source to sink, while reducing the number of states to a manageable amount. With a bit of care when modeling individual components, no implicit non-linear systems arise and the eigenvalues can be manipulated in a way that a fixed step solver can be utilized, resulting in hard real-time capability. The differential-algebraic nature of the approach is ideal to be solved by the index reduction techniques of Modelica.

Volume elements play a special role in the approach, as they act as additional boundaries for the fluid stream. Therefore we put much effort into robustly modeling them. We developed several volume models for different applications and applied regularization for reversed mass-flow and directly coupled volumes.

In this paper we give a short overview over the algebraic-differential stream-dominated approach (cap. 2), derive the equations of our standard volume while stating all assumptions, approximations and regularizations used for it to perform robustly (cap. 3), and finally explain the specialized volume models we implemented (cap. 4 and 5)

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and show applications examples (cap. 6). The Modelica code for all models and examples presented are publicly part of our open-source TFS Library.

2. ALGEBRAIC-DIFFERENTIAL THERMO-FLUID-STREAM NETWORKS

The directed thermo-fluid stream approach of Zimmer et al. (2018) uses streams of fluid masses ($\dot{m}$) that emerge from a source with a defined thermodynamic state. This state then is manipulated by an arbitrary number of components the stream passes, until it arrives at a sink that acts as a pressure boundary condition. These components might be pumps, flow resistances, combustion chambers, heat exchanges or any other device.

The mass-flow dynamics inside each component along a stream is governed by the equation

$$L\ddot{m} = \Delta r = r_\mathrm{o} - r_\mathrm{i} \tag{1}$$

where the inertance $L = \int \frac{ds}{A}$ is defined statically by the components area A along the flow direction s and Δr is the part of the pressure difference between inlet and outlet that results in an acceleration of the stream. This naturally leads to the definition of steady-state pressure $\hat{p} = p - r$ as the difference between static pressure p and inertial pressure r. Zimmer et al. (2018) defines the inertial pressure at each source as zero. Hence using (1), for a steady-state solution ($\ddot{m} = 0$), for each component along the stream r goes to zero and steady-state pressure is equal to the static pressure.

Zimmer et al. (2018) then uses the steady-state pressure instead of the static pressure to express the thermodynamic state of the stream at each component. While this simplification introduces some inaccuracies in the transients, the error is minute for typical applications and the simplification allows to separate the forward computation of the thermodynamic state (see fig. 1) from the linear mass-flow dynamics (1). This in turn allows the explicit computation of the non-linear equations governing the manipulation of the state (e.g. steady-state pressure and enthalpy) along the stream starting from the known state at the source. The inertial pressure at the sink is computed by the difference of the static pressure, that is the boundary condition at the sink, and the steady-state pressure arriving after passing through all components of the stream.

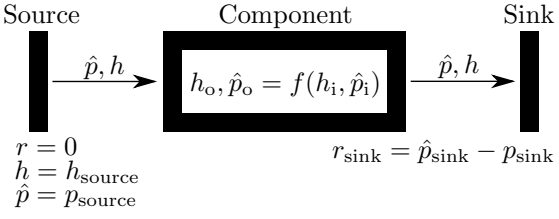

Fig. 1. Propagation of the thermodynamic state along a stream with boundaries $h_\mathrm{source}, p_\mathrm{source}$ and p_sink.

The result is a complex thermo-fluid network, that has no, or only very small non-linear equation systems, which are separated and localized within single components. For more details and how junctions and splitters of streams are implemented, we refer to Zimmer et al. (2018). Furthermore Zimmer (2019a) introduces an un-directed stream approach, with the same principle and Zimmer (2019b) adds several methods to make the solution more real-time capable.

Volume elements contain noticeable amounts of fluid. Here the state is governed by differential equations, and therefore cannot be modeled as simply manipulating a stream. Hence, volumes elements with pressure p_V and volume V play a special role in the approach, as they also act as boundaries for the stream: volume outlets (subscript o) are sources ($r_\mathrm{o} = 0$, $p_\mathrm{o} = \hat{p}_\mathrm{o} = p_\mathrm{V}$) and inlets (subscript i) are sinks ($p_\mathrm{i} = p_\mathrm{V}$) for the stream. This makes them particularly useful in closed loops, such as refrigeration cycles, where often a single volume is the only source and sink for the refrigerant, and therefore breaks the otherwise closed loop of the stream and makes it possible to compute the state explicitly from a source to a sink.

3. THE STANDARD VOLUME MODEL

In this chapter we first derive the equations for a simple volume model from first principle. We do that from the directed stream approach while stating which assumptions were used and then add some regularization for reversed mass-flow and direct coupled volumes.

3.1 Ideal Volume Equations

To derive the equations of an ideal standard volume, we assume that the medium within the model is ideally mixed (uniform pressure, temperature and composition). This allows us to depict the state of the fluid in the volume using only a few lumped states. For all mass-flows, enthalpy-flows or heat-flows a positive sign indicates the respective quantity entering the over the system boundary. This implies that the "correct" mass-flow for an outlet is negative. Furthermore we model heat-flow over the volume boundary which can be useful for modeling e.g. cooling systems or heat-flow into cryogenic tanks, but we don't model work going into the volume. The mass (M_j) balance (Baehr and Kabelac (1966)) for each component j of the fluid contained in the volume is the sum over the respective mass-flows into or out of the volume:

$$\dot{M}_\mathrm{j} = \sum_\mathrm{i} \dot{m}_\mathrm{j,i} \tag{2a}$$

with i mass-flows over the system boundary. Note that often the fluid consists of only one component.

The power balance equation for the volume with the above simplifications (Baehr and Kabelac (1966)) results in

$$\begin{aligned}\dot{U}_\mathrm{V} &+\dot{E}_\mathrm{V,kin} + \dot{E}_\mathrm{V,pot} = \\ &\sum_\mathrm{i} \dot{m}_\mathrm{i} \left(h_\mathrm{i} + \frac{c_\mathrm{i}^2}{2} + g z_\mathrm{i} \right) + \sum_\mathrm{k} \dot{Q}_\mathrm{k} - p_\mathrm{V} \dot{V}\end{aligned} \tag{2b}$$

with inner energy U_V, kinetic and potential energy of the volume $E_\mathrm{V,kin}$ and $E_\mathrm{V,pot}$, specific enthalpy, speed and height $h_\mathrm{i}, c_\mathrm{i}, z_\mathrm{i}$ of the i incoming or outgoing mass streams and k heat-flows $\dot{Q}_\mathrm{k}$.

We choose to neglect kinetic and potential energy of the fluid in the volume ($\dot{E}_\mathrm{V,kin} = \dot{E}_\mathrm{V,pot} = c_\mathrm{i} = z_\mathrm{i} = 0$), since they play only a minor role for our applications. The next simplification is that the wall (area A, temperature T_surf) temperature of the volume element is uniform and

the heat-flow into the fluid (temperature T_V) is governed by a simple heat-transfer with coefficient U:

$$\sum_\mathrm{k} \dot{Q}_\mathrm{k} = \dot{Q}_\mathrm{surf} = UA(T_\mathrm{surf} - T_\mathrm{V})$$

with a single heat-flow $\dot{Q}_\mathrm{surf}$ into the volume element.

Assuming a single inlet and outlet (subscripts i, and o) and using the overall mass in the volume $M = \sum_\mathrm{j} M_\mathrm{j}$ and specific inner energy u_V and specific enthalpy h_V of the volumes fluid ($U_\mathrm{V} = Mu_\mathrm{V}$), the power balance equation for a volume becomes

$$(\dot{Mu}_\mathrm{V}) = \dot{m}_\mathrm{i} h_\mathrm{i} + \dot{m}_\mathrm{o} h_\mathrm{V} + \dot{Q}_\mathrm{surf} - p_\mathrm{V}\dot{V} \tag{3}$$

The above equation assumes that outlet-streams state is the one of the fluid contained in the volume.

The thermodynamic state is defined by two state variables (Baehr and Kabelac (1966)). Since the above equations set only one, namely the specific inner energy u_V, we have to give a boundary condition on another state. A straightforward choice is fixing the volume V to a constant value and computing the medium's density from it, which together with u_V fully defines the state. This choice also eliminates the pressure-volume term in (3). In the following we will refer to this condition as the standard volume. Note that other choices of boundary conditions also are possible, as discussed in cap. 4.

Volume elements implement an inertance term (1) for all inlets and outlets, enabling mass-flow dynamics between directly connected volumes.

3.2 Regularization

Although we could use the above equations to accurately simulate a volume element, several numerical problems would arise. Firstly, even if the directed stream approach does not yield correct results for mass-flows against the flow direction, we want to have numerical stability for these conditions, since they might occur in dynamic simulations from time to time.

To illustrate the instability in the above equations, lets look at a steady mass-flow against the stream $0 > \dot{m} = \dot{m}_\mathrm{i} = -\dot{m}_\mathrm{o}$, no heat-flow and no pressure-volume work (fixed volume). With $\dot{M} = 0$ (2a) the energy balance (3) becomes

$$M\dot{u}_\mathrm{V} = |\dot{m}|(h_\mathrm{V} - h_\mathrm{i})$$

If the inlet enthalpy is smaller than the one in the volume, the fluid in the volume will heat up and vice versa, which both becomes exponentially unstable. To stabilize this, we simply set the enthalpy of the exiting stream h_o to h_i instead of h_V for reversed flow, basically disabling the energy equation. While this is not physically correct (correctness is not possible without state information of the fluid entering through the outlet - information not available in the approach), it is a stable behavior.

Secondly, if a volumes described as above gets connected to another volume or boundary without a flow resistance, the resulting mass-flow dynamics will lead in very fast and un-damped oscillations, which are highly undesirable. Zimmer (2019b) proposes to use a damping term only on the change of mass in the volume, instead of artificial flow resistances on inlet and outlet. This dampens these fast oscillations while not changing the steady-state solution. This damping term is added to (1) for the inlet and outlet of the volume:

$$\ddot{m}L = \Delta r - k\dot{M} \tag{4}$$

To determine the damping factor k, let us consider a volume, where the inlet is closed ($m_\mathrm{i} = 0$) and the outlet is directly connected to a sink (subscript s) with a constant static pressure boundary ($p_\mathrm{s} = \text{const}$, $\hat{p}_\mathrm{s} = \hat{p}_\mathrm{V}$). In contrast to Zimmer (2019b), we consider a general volume described by (2a) and (3). Using $r_\mathrm{o} = 0$, $p_\mathrm{V} = p_\mathrm{o} = \hat{p}_\mathrm{o} = \hat{p}_\mathrm{V}$ the inertial pressure difference at the outlet becomes

$$\Delta r = r_\mathrm{s} - r_\mathrm{o} = r_\mathrm{s} = p_\mathrm{s} - \hat{p}_\mathrm{s} = p_\mathrm{s} - p_V$$

Given this, a Taylor series expansion of first order of Δr with respect to the mass that has been flowing through the outlet m_o around the steady-state point ($\Delta r_0 = 0$) yields

$$\Delta r = \Delta r_0 + \frac{\partial \Delta r}{\partial m_\mathrm{o}} m_\mathrm{o} = -\frac{\partial p_\mathrm{V}}{\partial m_\mathrm{o}} m_\mathrm{o}$$

and hence with $\dot{M} = \dot{m}_\mathrm{i} + \dot{m}_\mathrm{o} = \dot{m}_\mathrm{o}$ (4) becomes

$$\ddot{m}_\mathrm{o} L = -\frac{\partial p_\mathrm{V}}{\partial M} m_\mathrm{o} - k\dot{m}_\mathrm{o}$$

When we assume only a small change of the volume V ($\frac{\partial p_\mathrm{V}}{\partial M} = \frac{\partial p_\mathrm{V}}{\partial \rho V} \approx \frac{1}{V}\frac{\partial p_\mathrm{V}}{\partial \rho}$), we can achieve critical or supercritical dampening therefore with

$$k >= 2\sqrt{L\frac{\partial p_\mathrm{V}}{\partial M}} \approx 2\sqrt{\frac{L}{V}\frac{\partial p_\mathrm{V}}{\partial \rho}} \tag{5}$$

The term $\frac{\partial p_\mathrm{V}}{\partial \rho}$ is determined by the choice of boundary condition of the volumes thermodynamic state. For the straightforward standard volume ($\dot{V} = 0$), it is determined by the media model. For other choices the term $\frac{\partial p_\mathrm{V}}{\partial M}$ will directly be derived in the next chapter.

The derivation at the inlet works analog and yields the same result as (5).

3.3 Un-directed Volume Elements

Zimmer (2019a) introduces an un-directed thermo-fluid stream approach. TFS implements the base components for un-directed flow, as well as connectors to combine directed and un-directed parts of the fluid network. The basic idea is to transport the thermodynamic state information in both directions along a stream and then decide which is the relevant one depending on the sign of the mass-flow. The latter is done using the "regstep" function, a smoothed jump between the two available states. For details of the theory and implementation in TFS we refer to Zimmer (2019a).

All volume elements discussed in this paper have a bidirectional counterpart with the same governing equations. The only notable difference is that the reversed mass-flow regularization introduced in the last section is no longer needed, since we have the information of the state the medium is arriving at the outlet.

4. NON-STANDARD VOLUME ELEMENTS

While the standard volume element described in the last chapter is suitable for many applications some others are still required.

4.1 Phase Separator

In almost any two-phase cycle (e.g. vapor cycle or Rankine cycle), accumulator and/or receiver models are used. These are tanks with fixed volume. If the medium in the phase separator contains two phases, it separates the phases and outputs either the liquid or the vapor phase, or a mixture. In our phase-separator model (see fig. 2) we assume, that the two phases are ideally separated and at ideal thermal equilibrium. Like the standard volume, it also has a fixed volume condition but additionally computes the vapor quality and the relative liquid level of it's medium l. With this and the upper and lower height of the outlet pipe $(h_{\text{low}}, h_{\text{high}})$, the relative liquid level in the outlet

$$l_{\text{pipe}} = \frac{l - h_{\text{low}}}{h_{\text{high}} - h_{\text{low}}}$$

and finally the outlet enthalpy

$$h_{\text{out}} = \begin{cases} h_{\text{liquid}}, & \text{for } l_{\text{pipe}} >= 1 \\ h_{\text{vapor}}, & \text{for } l_{\text{pipe}} <= 0 \\ l_{\text{pipe}} h_{\text{liquid}} + (1 - l_{\text{pipe}}) h_{\text{vapor}}, & \text{else} \end{cases}$$

are computed. Accumulators and receivers are both phase separator models, the first with a very high and the latter with a low outlet pipe.

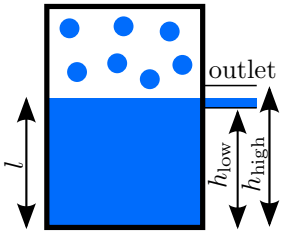

Fig. 2. Phase separator model. Inlet is not shown.

Similar to the standard volume the term $\frac{\partial p_{\text{V}}}{\partial \rho}$ is computed by the media model.

4.2 Flexible Volume

Closed loops of (nearly) in-compressible liquids could for example arise from a liquid cooling loop with water or glycol. Here the mass-flow-pressure differential equation becomes very stiff when using a standard volume, since between the fixed volume and in-compressiveness of the fluid there is no mechanism of budging when more mass must enter the volume. Zimmer (2019b) introduces a volume element with a compression module, basically a flexible tank that expands linearly with the pressure. It can also be seen as a linearisation of a fixed volume containing a gas bubble. The pressure the wall imposes on the fluid is linearly dependent on the volumes expansion with a reference point $(p_{\text{ref}}, V_{\text{ref}})$ and slope (bulk modulus) K:

$$p_{\text{V}} = p_{\text{ref}} + K\left(\frac{V}{V_{\text{ref}}} - 1\right) = p_{\text{ref}} + K\frac{M/\rho_{\text{V}}}{V_{\text{ref}}} - K \qquad (6)$$

This equation replaces the constant-volume condition of the standard volume. We also compute

$$\frac{\partial p_{\text{V}}}{\partial M} = \frac{K}{V_{\text{ref}}\rho_{\text{V}}}$$

for the dampening term (5). When this result is inserted into (5), the damping term is the same as derived in Zimmer (2019b) for a flexible volume.

4.3 Reservoir

A reservoir is a tank that is partially filled with fluid and partially with air from the environment. Therefore it's surface is in a pressure equilibrium with the environment. We assume that inlet and outlet are at the bottom of the reservoir, therefore the pressure at inlet and outlet are determined by environment pressure p_{env} and the mass of the fluid under earth gravity g. To simplify the equations we neglect the pressure gradient with height in the fluid. The static pressure of inlet, outlet and fluid therefore is

$$p_{\text{V}} = p_{\text{env}} + \frac{Mg}{A_{\text{V}}}$$

From this we can compute

$$\frac{\partial p_{\text{V}}}{\partial M} = \frac{g}{A_{\text{V}}}$$

for the regularization. Note that the reservoir can be seen as a special case of the flexible volume with $K = \frac{gV_{\text{ref}}\rho_{\text{V}}}{A_{\text{V}}}$ and $p_{\text{ref}} = p_{\text{env}} + K$

4.4 Mixing Volume

Junctions of fluid streams as defined in Zimmer et al. (2018) make simplifications that, although good enough for most cases, might influence the result at transient conditions if the application requires very accurate mixing behavior. For such applications we implemented a volume with an arbitrary number if inlets. The dampening term is applied to all inlets simultaneously. Other than that the mixing volume is a standard volume. In contrast to a junction, the mixing volume does not have to use approximations in mixing and is also accurate for fast transients.

5. THE CONDUCTION ELEMENT

Heat exchangers that evaporate or condensate a working fluid pose a challenge in modeling, since the classic ϵ-NTU method (Incropera et al. (1996)) does not apply, and because the fluid has very different properties in its liquid, gaseous or 2-phase form. In TFS we include a discretized heat exchanger, that thermally couples N volume elements on each path in cross- and counter-flow configurations (see fig. 3). The volume of each element is computed by dividing the heat exchangers volume by N, resulting in many very small volumes in a row. Even with the dampening term introduced in 3.2 or when we introduce discretized flow resistance models between the volumes to simulate the pressure drop within the heat exchanger, we get a (with these measures damped but) very fast mass-flow-pressure dynamics between the very small volumes resulting in a very stiff simulation.

Since our scope is a medium-fidelity simulation on system level, we are not interested in the mass-flow dynamics within the heat exchanger and would rather have a single fluid stream going through it. Because of this, we simplified the standard volume model to what we call a conduction element, replacing the mass balance (2a) by directly coupling inlet and outlet mass-flow ($\dot{m} = \dot{m}_{\text{i}} = -\dot{m}_{\text{o}}$) and implementing (1) between inlet and outlet. Without the information of the mass dynamics, we assume the mass to

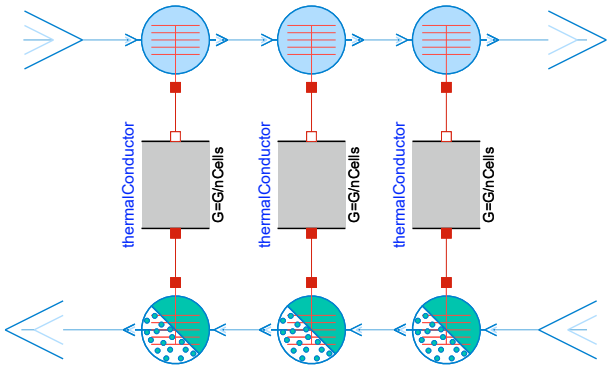

Fig. 3. Discretized counter-flow heat exchanger with three elements in Modelica. The lower conduction elements compute the heat transfer coefficient to the wall depending on the phase of the liquid contained.

be quasi-stationary (with $\dot{M}$ small enough to be negligible for our modeling purpose and $M = V\rho_V$) depending on volume and density of the liquid ρ_V. To investigate the influence of this assumption on the power balance (3) we first look at its left-hand side:

$$(\dot{M u_V}) = (\dot{M(h - p_V V)}) \approx (\dot{M h_V}) = \dot{M} h_V + \dot{M} h_V \quad (7)$$

Here we made use of the fact that V is constant and neglect the volume-pressure term $\dot{p}_V V$ (which didn't show noticeable impact on our simulation results) to arrive at a equations in the enthalpy h_V instead of the inner energy u_V. This simplifies the interaction with the media models. The other option would be to include the pressure-volume term on the right-hand side, but this would require the pressure to be differentiable which is not always the case in our simulations. On the right-hand side enthalpy-flow terms for inlet and outlet are of interest. With $\dot{m}_i + \dot{m}_o = \dot{M}$ they can be expressed as:

$$\begin{aligned} \dot{m}_i h_i + \dot{m}_o h_V &= \\ \dot{m}_i h_i + (\dot{m}_o + \dot{m}_i - \dot{m}_i) h_V &= \dot{m}(h_i - h_V) + \dot{M} h_V \\ (\dot{m}_i + \dot{m}_o - \dot{m}_o) h_i + \dot{m}_o h_V &= \dot{m}(h_i - h_V) + \dot{M} h_i \end{aligned}$$

these two solutions pose the edge cases of whether we want to attribute the changes in mass we neglect to an additional inlet or outlet mass-flow. In general the solutions should lie somewhere in the middle, so with $k \in [0, 1]$ we can state the full right-hand side of the power balance (3) for quasi-stationary mass as

$$\dot{m}(h_i - h_V) + \dot{M}(h_V + k(h_i - h_V)) + \dot{Q}_{surf}$$

and with (7) derive the power balance for the conduction element:

$$\dot{M} h_V = \dot{m}(h_i - h_V) + \dot{M} k(h_i - h_V) + \dot{Q}_{surf} \quad (8)$$

The term $\dot{M} k(h_i - h_V)$ poses several problems. Firstly, it requires the mass to be differentiable, which might be violated e.g. for a step in pressure. Secondly, k is an unknown time dependent variable and thirdly, it has shown to lead to numerical problems in practice. Luckily, its impact is mostly neglectable, so we can neglect changes in mass in (8) ($\dot{M} = 0$). The disadvantage of this is an error in the power balance when the mass in the volume is changing, that can be noticeable when the change is drastic (e.g. during phase transitions of the fluid).

Naturally, without mass dynamics the conduction element does not need the mass-flow dampening but still needs the regularization for the reversed mass-flow condition introduced in cap. 3.2. In fact, it was while working with conduction elements, that the instability of the reversed mass-flow condition became apparent for the fist time.

While the modeling approach of the conduction element might not be suited for high fidelity modeling tasks that involve major mass transitions, like optimal charge determination or accumulator/receiver sizing, its simplicity offers big advantages, for high-level simulations. It introduces only a single state without adding fast mass-flow dynamics while still being a good proxy for a volume, depicting the energy balance and therefore the dynamics of heat transfer. This is why we use it very frequently to transfer heat in and out of fluid stream. If a higher fidelity model is needed the conduction element can be replaced by standard or flexible volumes.

It is to be noted that the conduction element is part of a fluid stream and no longer acts as a stream boundary. It therefore can not be used to break a closed fluid loop.

6. APPLICATION EXAMPLES

In this section we present some application examples of the volume models developed in the last chapters in dynamic simulations. All examples are part of our Modelica library (Zimmer et al. (2021)) and hence their implementation is available open-source. In the examples' images, we removed all control elements and most flow resistance models for better readability.

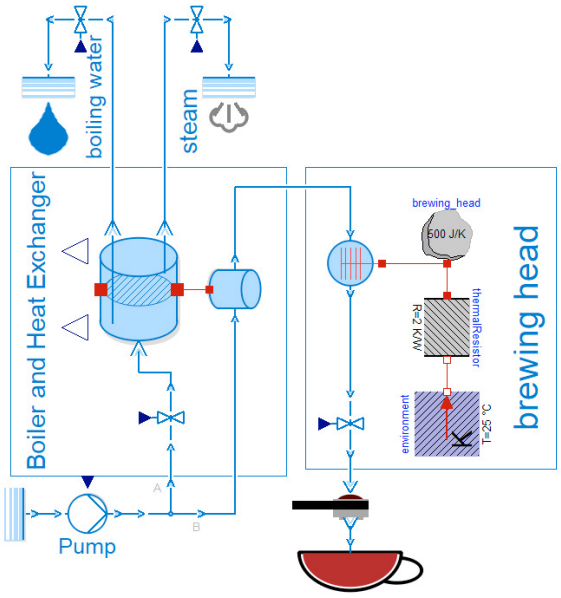

Fig. 4. Model of a espresso machine. The boiler is implemented especially for this model, but is conceptually very close to the phase separator. The brewing head is in thermal contact with the environment. The cup is internally modeled as a Sink.

In fig. 4 the standard volume heats up water going to the brewing head by being in thermal contact to the boiler. Another standard volume is used in fig. 5 to put heat into the heat engine.

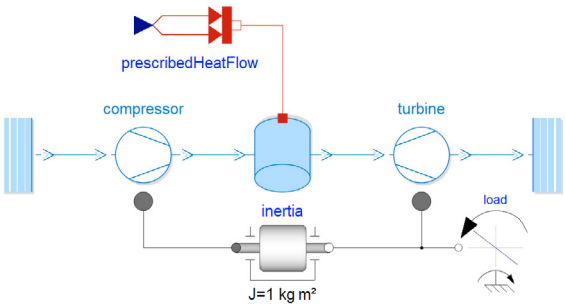

Fig. 5. Basic heat engine model. Air enters at the source, gets compressed in a compressor, heated up in a standard volume, gets de-pressurized in a turbine and exits at environment pressure at the sink.

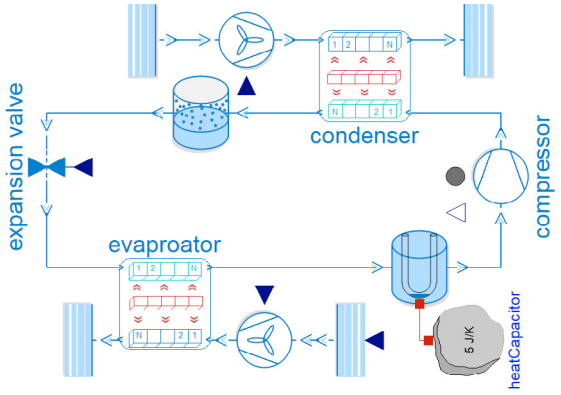

Fig. 6. Heat pump model consisting of two air-streams and a two-phase loop with accumulator, compressor, condenser, receiver, expansion valve and evaporator.

The phase separator is the basis for the accumulator (high outlet pipe position) and receiver (low pipe outlet position) in the heat-pump depicted in fig. 6. While the receiver is adiabatic ($Q_{\text{surf}} = 0$) the accumulator is connected to a heat capacity. Note that this looped stream is broken into two streams by the two volumes.

The liquid cooling example (see fig. 7) needs a flexible volume to break the loop, since its medium is in-compressible. An alternative would have been a reservoir, as it is a special case of a flexible Volume.

The conduction element is used in figs. 4 and 7 to exchange heat with the fluid. In the former to exchange heat between brewing head fluid, in the latter to cool the heat-load. Furthermore in fig. 6 both heat exchangers are discretized ones that use multiple conduction elements to exchange heat between the fluids.

7. CONCLUSION

In this paper we derived a number of volume elements that can be used in the algebraic-differential thermo-fluid stream approach to simulate complex thermo-fluid networks. While deriving the equations from first principle, we stated all approximations and assumptions taken to optimize the models to the algebraic-differential thermo-fluid-stream approach. All models developed are part of our TFS Modelica library and their source-code is therefore publicly available. With these volume models

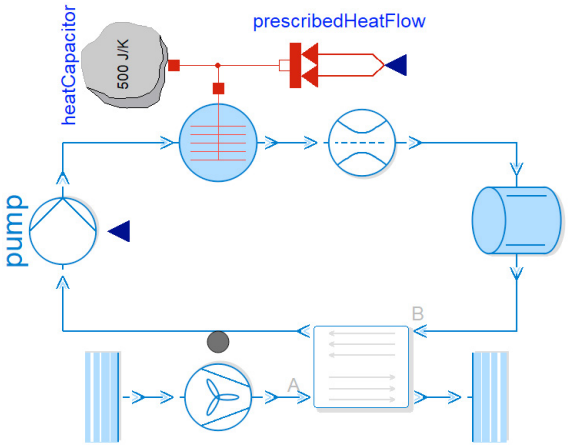

Fig. 7. Simple liquid cooling loop. The in-compressible fluid exits the flexible volume, passes a conduction element that is used to cool a heat load, passes a flow resistance, goes through a ϵ-NTU heat exchanger, a pump and flows back into the volume. The heat load is modeled by a heat capacity and prescribed heat-flow. The heat exchanger is cooled by a cold air stream.

within the library and using the Modelica Standard Media Models, we are able to model a broad range of applications, some of which we presented in the last section of this paper.

We will continue to use our library and with it the volume models presented in our future scientific work, further validating the usefulness of the models presented.

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