# Simulation of Components of a Thermal Power Plant

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## Abstract

In this paper different models for simulating components of thermal power plants and other thermal or thermodynamic processes are presented. The different simulation results were performed with *Dymola* which is based on *Modelica*. The models were realized with time domain differential equations and algebraic equations. For all components the fluid was modeled by using the *Modelica.Media* library which is part of the *Modelica* standard library.
The heat transfer for the heat exchanger component was modeld by calculating the heat transfer coefficient in dependency on the flow velocity of the medium in the pipes.

## 1 Introduction

Arsenal Research currently works on the developement of a simulation library for thermal and thermodynamic processes. Elementary problems like heat transfer and fluid dynamics will be processed. To a large extent the *Modelica_Fluid* library already covers a lot of important models, which are used to develop parts of thermal power plants. The new library will complete the *Modelica_Fluid* library. Some of the presented models are based on components of the *Modelica.Fluid* library. For some special technical problems the *Modelica_Fluid* library was modified and extended.

## 2 Extended models to be developed

Arsenal Research is working on specific problems related with heat transfer and fluid dynamics. The development of the following components is currently initiated:

- Centrifugal pump
  - An ideal pump based on physical parameters
  - A pump with losses based on physical parameter
- Simple pipe comprising pressure losses
- Heat exchanger including pressure losses, thermal convection, thermal conduction
- Turbine modeled with a characteristic curve

## 3 Components

### 3.1 Fluid flow machines

In a thermodynamic processes or thermal power plant fluids and different gases have to be transported through pipes. Pipes cause pressure losses. To generate a constant mass flow, pumps are needed. Yet, in some cases stationary density differences give rise to a constant mass flow without having a pump, like in a natural circulation boiler. For assistance or to start a fluid flow, pumps are the most important components in thermal processes. Pumps are fluid flow machines. Mechanical shaft energy is transformed into kinetic and potential flow energy. The impeller which is directly attached on the shaft, accelerates the fluid elements. Because of the diffuser effect in the shovel channels of the impeller wheel, the operating fluid leaves the impeller with increased pressure. Pumps represent a link between pressure increase and flow velocity or the mass flow. This context leads to the characteristic of a pump. Each pump typ has its typical characteristic in dependency on its geometry and rotation speed.

#### 3.1.1 Ideal centrifugal fluid flow machines

An ideal pump is a fluid flow machines with an infinite number of shovels. The converted energy in the

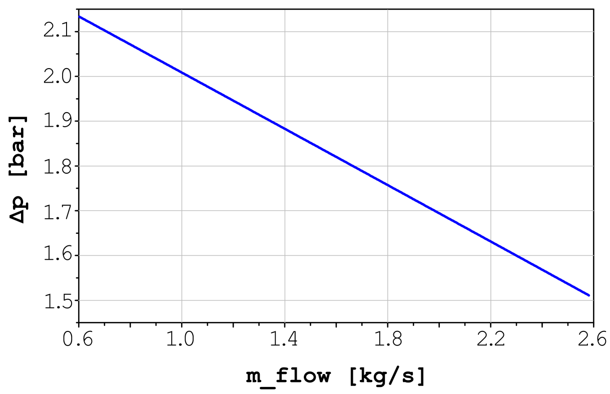


Figure 1: Characteristic of an ideal water pump

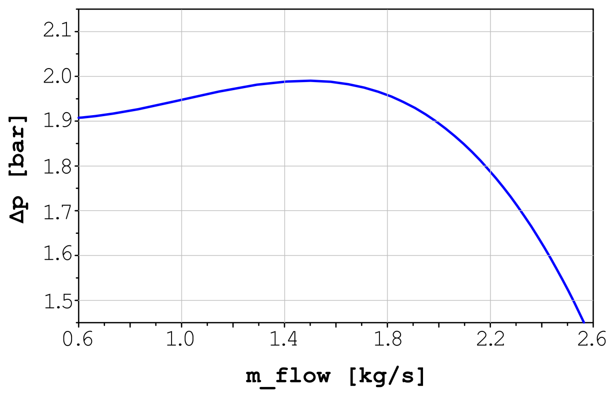


Figure 2: Characteristic of the cetrifugal water pump with losses

impeller wheel of the water pump is the kinetic and potential energy of the operating fluid. Therefore the main equation of the water pump represents the proportion between mechanical energy of the input shaft with respect to the impeller wheel of the water pump and the specific energy of the operating fluid [1].

$$\dot{m} \cdot \omega = 2 \cdot \pi \cdot b_2 \cdot \rho \cdot \tan(\beta_2) \cdot (r_2^2 \cdot \omega^2 - Y_\infty) \qquad (1)$$

In this equation $r_2$ is the outer radius of the impeller wheel of the water pump, $b_2$ is the outer width of the impeller wheel, $\rho$ is the density of the operating fluid and $\beta_2$ is the outlet angel of the shovel of the impeller wheel. Furthrmore, $\dot{m}$ represents the mass flow of the operating fluid in the water pump and $Y_\infty$ represents the specific energy of the impeller wheel for an infinite number of impeller shovels. The ideal pump model was implemented *Modelica* using *Dymola* as simulation tool. Figure 1 shows the linear characteristic of the ideal water pump. Pumps as a special fluid flow machines is detailed processed in [2].

### 3.1.2 Centrifugal Pump

In realistic pumps, friction, fluid impacts and other fluid dynamic effects cause losses in the water pump. These losses can be split into:

- Decrease of the specific energy
- Hydraulic losses in shovel channels
- Impact losses
- Friction losses of the impeller wheel

A perviously developed model of an ideal pump [3] was used to design a water pump with losses. The new model now uses the *Modelica.Media* library to model the fluid. Figure 2 shows the characteristic of this model.

## 3.2 Initialization

In real thermal power plants, some components, like the turbine, have to be brought up to operational conditions by a well defined starting procedure. Reasons for this starting procedure can be load limits of certain components, cavitation of operating fluids or restriction due to the process.

In computer simulations, certain start values define the initial state of the simulation. Therefore, a simulation usually can be started from any state. From the particular starting point, the system should then reach a steady state condition. The initialization of a complex model becomes more difficult when using the *Modelica.Media* library.

The *Modelica.Media* library has certain operational limits. Outside these limits an error occurs. For example, the start-up procedure of a real pump is very complex. At the suction side of the pump the pressure decreases during the start-up procedure. Without controlling the process of starting up a simulation, like in a real system, an error may occur. This, however, may lead to a complex controlling due to the huge number of physical quantities to be controlled.

### 3.3 Pipe as an important part of Heat Exchangers

The pipe is one of the most elementary components. A lot of thermal power plant components are based on simple pipe models. One of these important components is the heat exchanger.
In a real pipe, the pressure drop of a fluid flowing through the pipe, decreases due to the wall roughness of the surfaces. The pressure drop also depends on the flow velocity and on the roughness of the inner surface of the pipe. The cross-section of the pipe also influences the pressure losses. For circular pipes the pressure drop can be calculated according to:

$$\Delta p = \lambda \cdot \frac{L}{D} \cdot \frac{\rho \cdot v^2}{2} \tag{2}$$

The pressure drop $\Delta p$ is a function of a coefficient of friction, $\lambda$, the length of the pipe, $L$, the characteristic length, $D$, the density, $\rho$, and the velocity, $v$. The coefficient of friction, $\lambda$, depends on the *Reynolds* (*Re)* number. The *Re* number is defined by (3). The *Re* number defines the type of flow. The flow can be turbulent, laminar or in the transient area.

$$Re = \frac{v \cdot D}{\nu} \tag{3}$$

The pressure drop substantially depends on the flow type. For the laminar area applies:

$$\lambda = \frac{64}{Re} \tag{4}$$

For the turbulent area basically applies:

$$\frac{1}{\sqrt{\lambda}} = -2 \cdot \log\left(\frac{2.51}{Re \cdot \sqrt{\lambda}} + \frac{k}{3.71 \cdot D}\right) \tag{5}$$

In this equation $k$ is the roughness of the inner pipe surface. Figure 3 represents $\lambda$ versus the *Re* number for different flow types.
The *Modelica_Fluid* library contains a lot of different pipe models with different levels of abstractions. Arsenal Research develops extended models based on the components of the *Modelica_Fluid* library. Simultaneously, Arsenal Research developed simplified models for easy handling and modeling of test cases, incorporating less parameters than the comprehensive models. *Modelica_Fluid* and the extended and the simplified models are using the same basic equations, with respect to e.g. friction models, Reynolds equation, etc.

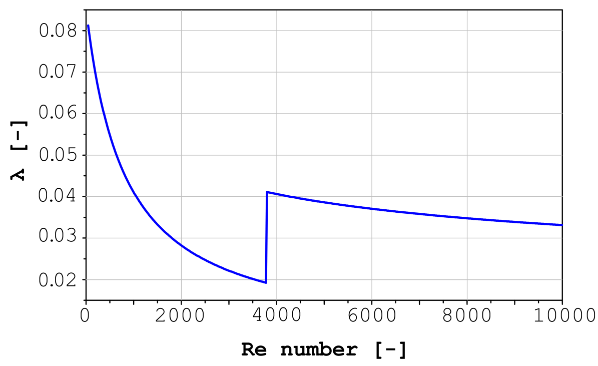


Figure 3: Coefficient of friction versus different flow types

Figure 4 shows the pressure drop versus *Re* number. The discontinuity indicates the transition from laminar (at low *Re* numbers) to turbulent fluid flow (at high *Re* numbers).

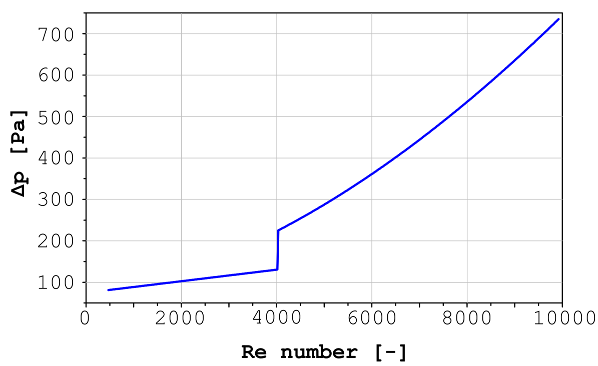


Figure 4: Prssuredrop in pipes versus flow velocity

### 3.4 Heat Exchanger

Heat Exchangers are very important for nearly every thermal process. In heat exchangers usually two interacting fluid circuits are involved. The temperatures of both fluids are approaching. Yet a certain temperature difference is required to maintain the energy flow from the higher temperature fluid to the lower temperature fluid. Figure 7 shows a scheme of a pipe heat exchanger.

#### 3.4.1 Heat propagation in Fluids

For modeling a heat exchanger it is necessary to understand how heat propagation in fluids works. Heat propagation is described with partial differential equations in one dimension [4] . In standing fluids heat is transported by diffusion. The diffusivity $a$ depends on the operating fluid. The thermal conduction equation for one dimension is shown in (6). In this equation $q$ is an additional heat source, $T$ is the temperature and $x$ is the location. The diffusivity $a$ is a fluid property, which is a function of the heat conduction $\lambda$, the density $\rho$ and the specific heat capacity $c$, according to (7)

$$\frac{\partial T}{\partial t} = a \cdot \frac{\partial^2 T}{\partial x^2} + q \qquad (6)$$

$$a = \frac{\lambda}{c \cdot \rho} \qquad (7)$$

In flowing fluids the heat is also transported with the flowing medium, which depends on the fluid velocity. This leads to a remodeling of the heat propagation (6). Properties in a hydrodynamic flow depend on time and location. The temperature is the important property in this case. So the temperature depends on the time and the place in the pipe. The total differential of the temperature with respect to the time and the place has to be calculated according to (8). To substitute this context into (6) it is necessary to have an expression [5] for:

$$\frac{\partial T}{\partial t}$$

So function (8) has to be divided by $dt$.

$$dT = \frac{\partial T}{\partial t} \cdot dt + \frac{\partial T}{\partial x} \cdot dx \qquad (8)$$

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + v \cdot \frac{\partial T}{\partial x} \qquad (9)$$

After summarizing equation (9) and (6) we receive an equation for the heat transport in axial direction:

$$\frac{\partial T}{\partial t} + v \cdot \frac{\partial T}{\partial x} - a \cdot \frac{\partial^2 T}{\partial x^2} = q \qquad (10)$$

### 3.4.2 Heat Transfer caused by Convection

To design a heat exchanger model, different physical effects have to be considered. It is necessary to know the quantity of heat flow which is transported from a fluid in the pipe to the outside surface. The heat transfer between the fluid and the pipe wall has to be modeled. This heat transfer happens by means of convection. The heat transfer coefficient describes the heat transfer between fluid and pipe wall, and is defined by the *Nusselt (Nu)* number according to (11). The *Nu* number is, however, a function of the *Re* number and of the medium properties. The *Re* number describes the type of flow (laminar, turbulent) and therefore, also the *Nu* Number depends on the type of flow.

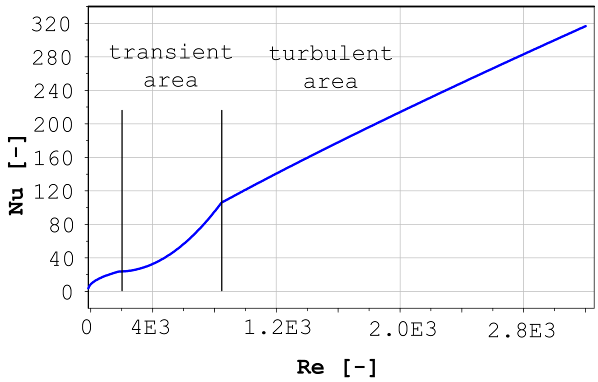


Figure 5: Nu number versus increasing flow velocity

$$Nu = \frac{\alpha \cdot L}{\lambda} \qquad (11)$$

To determine out the quantity of heat, flowing between the fluid and the pipe wall, the Nusselt-Number has to be calculated. To transfer high quantities of heat flow high *Re* numbers are necessary. Figure 5 shows the *Nu* number versus the *Re* number.
The heat transfer coefficient $\alpha$ increases with increasing *Re* number. A salient turbulent flow is important to have a high quantity of heat transfer. In turbulent areas the heat transfer increases linear with the *Re* number [6].

### 3.4.3 Heat Transfer caused by Diffusion

As in shown in (6), the diffusivity is responsible for the heat propagation in fluids. The *Peclet (Pe)* number is the proportion between convective heat transport and heat transport through conduction:

$$Pe = \frac{d \cdot v}{a} = Re \cdot Pr \qquad (12)$$

The Peclet-Number determines whether the diffusion is substantial or can be neglected.

### 3.4.4 Model of a Pipe

To design a detailed model of a heat exchanger, the model should consider all the above described physical behaviors. Different types of heat exchangers lead to different results. Every different types of heat exchanges needs different equations to describe the physical coherence.

- Parallel flow heat exchangers
- Counter flow heat exchangers
- Cross flow heat exchangers
- Plate heat exchangers

Each type of heat exchanger has a different efficiency because of their different heat transfer behavior. In *Modelica* continuos heat transfer is modeled by heat transfer between $n$ infinite small pipes. Where $n$ is the number of elements. To get a model of a heat exchanger, an infinite small pipe segment could be the main model. A simply unlagged pipe always has a heat transfer with the environment. Figure 6 shows a model of an infinite small pipe segment. The component `pipe`, models the pressure drop in this infinite small segment. The pressure drop is caused by the friction between the fluid and the inner wall of the pipe. The additional connector is a real vector of the size 5. This connector transmits the pressure $p$, specific enthalpy $h$, massflow $m\_flow$, segment length $L$ and the characteristic length $d$ to the component `heat transfer`. The characteristic length is for a circular cross-section the diameter. The component `heat transfer` needs the parameter to calculate the $Nu$ number, which defines the heat transfer coefficient $\alpha$ for an infinite small area. To get the whole heat transfer through a pipe surface, $\alpha$ has to be multiplied with the pipe surface $A$ according to (14). The model `heat transfer` transmits $G_x$ to the component `convection`. Now the energy flow $Q_x$ between fluid and the pipe wall in radial direction caused by convection can be calculated by:

$$Q_x = G_x \cdot \Delta T \qquad (13)$$

$$G_x = \alpha \cdot A \qquad (14)$$

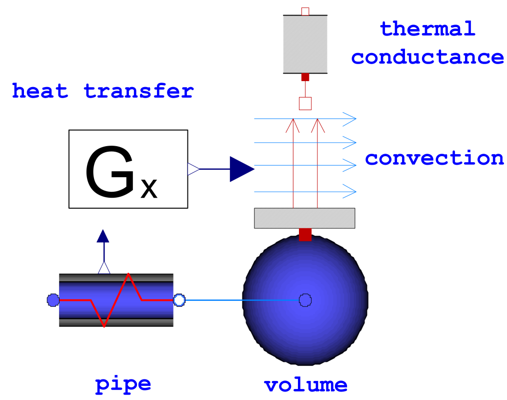


Figure 6: Model of an infinite small pipe segment

The component `thermal conduction` simulates the heat conduction through the wall of the pipe. The red line which is drawn in in the component `pipe` in Figure 6, indicates the heat transfer in axial direction caused by diffusion. The influence on heat propagation caused by diffusion is negligible small. High $Pe$ numbers show that for usual technical applications the diffusion can be neglected. To minimize the *CPU*-Time, diffusion was not implemented in the heat exchanger model. At the outer port of `thermal conductance` an additional heat source could be simulated, considering e.g. solar radiation or a cooling environment.

### 3.4.5 Model of a Heat Exchanger

In a heat exchanger, a second fluid constitutes an additional heat source. Figure 7 shows the scheme of a parallel heat exchanger. The second `fluid A`, circumflows the pipe which contains the `fluid B`. Heat flow interchanges between both fluids. The heat flows from the fluid with higher temperature to the fluid with lower temperature. In a parallel heat exchanger the fluids flow in the same direction. At the inlet the temperature gradient is on its highest level and decreases towards the flow outlet. The temperatures of both fluids are approaching. Figure 7 shows that heat flow is transported from the hot `fluid A` to the second `fluid B`. The pipe has a mass which also has to be heated up, and therefore, the heat capacity of the pipe has to be considered. The efficiency of a heat exchanger is at its maximum, if the heat flow between both fluids is as high as possible. For this reason it is important that the pipe is a good heat conductor. The

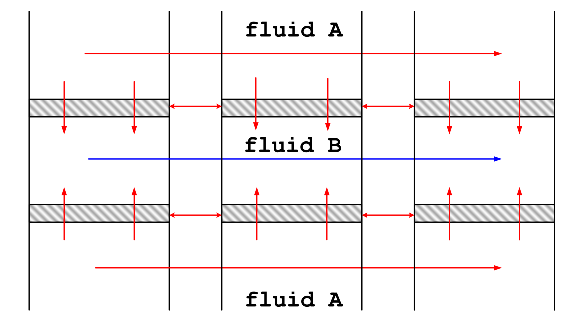


Figure 7: Scheme of a parallel tube heat exchanger

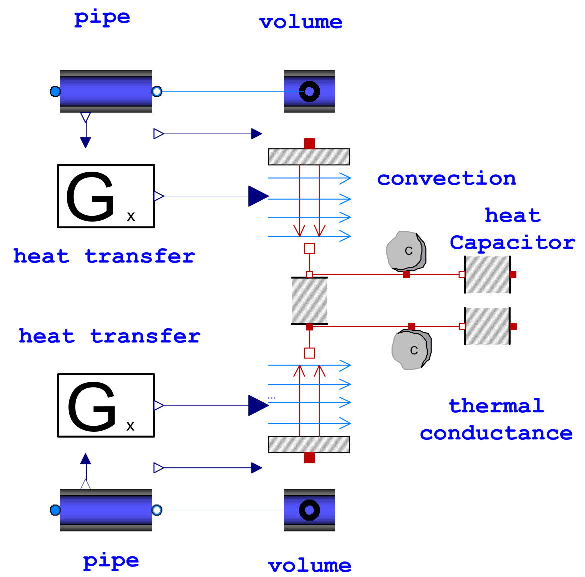


Figure 8: Model of a segment of a parallel heat exchanger

wall of the pipe conducts heat also in axial direction. This has to be respected in the heat exchanger model, because for some types of heat exchangers, this effect is very important. Figure 7 shows a scheme of a parallel pipe heat exchanger and Figure 8 shows the implementation in a *Modelica* model.
Figure 8 shows the model of an infinite small element of a finitely long parallel tube bundle heat exchanger. The model `volume` is directly taken out of the *Modelica_Fluid* library. It was equipped with an additional connector. This connector transmits some geometrical parameter of the pipe to the `volume`, so that the volume of the pipe segment can be calculated. The additional components, `conduction` and `capacity`, model the pipe with heat conduction in axial and radial direction. For a parallel heat exchanger these components do not have a significant effect. The second `heat transfer` component simulates the heat flow, which is transmitted form the outer fluid to the pipe. In the heat exchanger model the number of elements and the length of the whole pipe bundle has to be specified.
The model of one segment is connected $n$ times one after another to model a whole heat exchanger. Figure 9 shows the temperature versus the length of the heat exchanger. This is an result taken out of a simulation with only 10 element. The model contains over 2000 algebraic and differential equation.

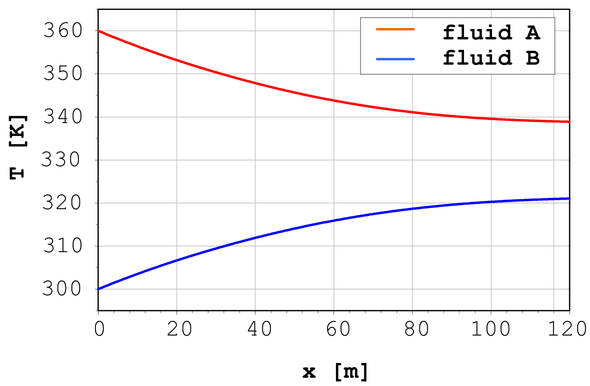


Figure 9: Temperature distribution inside the heat exchanger

## 4 Conclusion

Simulations of components of thermal power plants or of other thermal processes are very complex. Especially the consideration of the complex media of the

*Modelica.Media* library leads to very detailed models and precise results. Nevertheless, the *Modelica.Media* library allows for a high precision of results. For some applications, however, it makes sense to model some components with a more simplified level of abstraction. Therefore it is necessary to carefully decide on the detail of abstraction for each model.

## Abbreviations

CPU central processing unit

## References

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