

Study of humidification and condensation dynamics in an evaporative gas turbine cycle

M.Sc. Thesis
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Abstract

The electricity demand is forecasted to increase during the next decades, especially in the developing countries. Renewable power production technologies are promising, though they are not expected to be able to satisfy the complete future need. Therefore the Evaporative Gas Turbine, EvGT, is assumed to be a good complement to renewable power sources. There are also ongoing experiments about using renewable fuels in an EvGT.

The EvGT project is a co-operation between universities, gas turbine manufacturers, utility power companies, and research organisations in Sweden. It started in 1989 and since then an evaporative gas turbine pilot plant has been built at LTH to demonstrate the technology. The project has finished three phases and is now in phase four. Read more about the project in (Rosén, 2000).

Sydkraft AB is one of the members of the EvGT project, to whom Sycon Energikonsult AB has performed technical work. The contribution of Sycon Energikonsult AB has included modeling of the EvGT model. The gas cycle in the EvGT process has been modeled and the flue gas condenser is the missing component to close the water cycle.

The objective of this thesis has been to study the evaporative and condensation process of the EvGT cycle by means of modelling and simulating two components, the humidification tower and the flue gas condenser.

One conclusion is that the same model can be used as a humidification tower and as a condenser. The difference that defines humidification respectively condensation is the temperature of the gas and water, and the pressure. These temperatures are derived from measurement values from the pilot plant at LTH.

The most critical part when modelling was found to be the evaporation or condensation, i.e. when water changes phase between liquid and gas. To further improve the model this is where the effort should be made.

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Terminology

<i>Condensate</i>	Water that before the condensation process was water vapor.
<i>Condensation</i>	The process where water vapour is transformed into water.
<i>Conduction</i>	Heat transfer between two substances, for example water and copper.
<i>Convection</i>	Heat transfer between a solid surface and a gas or liquid that is in motion. Convection involves the combined effects of conduction and fluid motion.
<i>Diffusion</i>	The process where a soluble substance is solved and mixed with another one.
<i>Dymola</i>	The simulation tool that has been used during the thesis work.
<i>ENERGY</i>	Sycon's library of thermodynamic models.
<i>Evaporation</i>	The process where water is transformed into water vapor.
<i>EvGT</i>	Evaporative Gas Turbine.
<i>Water Film</i>	Representation of the interface between gas and water.
<i>Humidification</i>	The process when gas is humidified with water vapour.
<i>LTH</i>	Lunds Tekniska Högskola.
<i>Mantle wall</i>	The outermost wall of a real component in the EvGT cycle.
<i>Package</i>	Material used in the condenser and humidification tower to increase the area between gas and water.
<i>Validation</i>	Comparing of the simulation results with real measurement values from the pilot plant.
<i>Verification</i>	Evaluation of the simulation results to see if the model seems to behave as desired.

1 Introduction

This chapter describes the background of the thesis. It explains the need of gas turbines, the EvGT project and the part Sycon Energikonsult AB plays in the project. Finally, the purpose and erection of this thesis will be handled.

1.1 Background

What is EvGT?

The Evaporative Gas Turbine (EvGT) is an example of a wet gas turbine cycle, also called water vapour addition cycle. This means that compressed air mixed with water vapour is used in the gas turbine. Sometimes the evaporative gas turbine is called HAT, Humid Air Turbine. This is a patented variant of EvGT. Another example of the technology with humid air is STIG, Steam Injected Gas turbine. More about wet cycles can be read in (Ågren, 2000).

The electricity demand is forecasted to increase during the next decades, especially in the developing countries. Renewable power production technologies are promising, though they are not expected to be able to satisfy the complete future need. Therefore the Evaporative Gas Turbine, EvGT, is assumed to be a good complement to renewable power sources. There are also ongoing experiments about using renewable fuels in an EvGT.

For long-term electricity and heat production the aspects of pollution and efficiency are important. Today's electricity producing gas turbines have a satisfying efficiency but the pollution is too high. The evaporative gas turbine has shown to be a good alternative to keep the NO_x discharge low. The characteristic of the cycle is that water is evaporated at a low temperature to increase the humidity of the combustion air. The result of this evaporation is higher efficiency and lower NO_x discharge, which is highly desired. To close the water cycle and reuse the added water a flue gas condenser is used.

The EvGT project

The EvGT project is a co-operation between universities, gas turbine manufacturers, utility power companies, and research organisations in Sweden. It started in 1989 and since then an evaporative gas turbine pilot plant has been built at LTH to demonstrate the technology. The project has finished three phases and is now in phase four. Read more about the project in (Rosén, 2000).

The overall purpose of the project is to evaluate the evaporative gas turbine technology. The erection of the pilot plant was used to determine efficiency, pollutants, and dynamic behaviour. It also helped identify the potential of the cycle.

Modelling the EvGT

Modelling is a way to reduce problems with simplifying complex relationships. The modelling is especially useful for verifying requirements and process optimization. Modelling also reduces the risk of problems when the component is put into operation. This of course saves a lot of money and time.

Sydskraft AB is one of the members of the EvGT project, to whom Sycon Energikonsult AB has performed technical work. The contribution of Sycon Energikonsult AB has included modelling of the EvGT model. The gas cycle in the EvGT process has been modelled and the flue gas condenser is the missing component to close the water cycle.

The flue gas condenser resembles a humidification tower, which is another component in the EvGT cycle. This tower has been modelled but a validation of it, i.e. to make the model fit the measurements from the pilot plant at LTH, is needed. This is done by means of measurements from the pilot plant. After the validation the flue gas condenser can be modelled on the basis of the humidification tower, after which it can be verified. Verification means to check that the model works as desired. Since real measurement values are missing a validation of the flue gas condenser can not be done.

The modelling tool used at Sycon Energikonsult AB is Dymola¹. The modelling language of Dymola is Modelica. This is an object oriented language, which makes exchange and reuse of different models possible. Dymola includes a standard library consisting of e.g. mathematical functions, mechanical components, and electrical components. Sycon Energikonsult has also built its own library, ENERGY. The library contains useful components for thermodynamic modelling like gas volumes, flows, and heat exchangers. In Chapter 4 more information about Dymola and ENERGY can be found.

1.2 Objective

The objective of this thesis is to validate the already existing humidification tower model with measurement values from the pilot plant at LTH. The validation mainly includes static values.

The next goal of the thesis is to build a model of the flue gas condenser on the basis of the humidification tower. A decision has to be made whether the condenser should be a wet or dry one, of which the differences are explained later on in the thesis. The flue gas condenser is built with Sycon's ENERGY library to make it possible to connect with the already existing models. The model needs to be verified for reliability with both static and dynamic values.

¹ More about Dymola at www.dynasim.se

1.3 Organisation of the report

In Chapter 2 there is a short description of the work done during the time at Sycon Energikonsult AB. It will handle what was done, why, and in what order.

Chapter 3 describes the basics about the evaporative gas turbine cycle.

Chapter 4 explains the facts necessary to understand the two following chapters. The basic equations used when modelling are explained in Chapter 4.1 while the basics about the modelling tool Dymola are explained in Chapter 4.2.

The following chapter, Chapter 5, will handle the humidification tower; first a description of how it works in reality, and later an explanation of the model of the tower. After that in Chapter 5.3 the validation work is treated. Similar work as for the humidification tower is done for the flue gas condenser in Chapter 6.

Chapter 7 summarises what can be further done on the models, problems that have occurred during the work, and an analysis of how well the created model is working was treated.

The last Chapter 8 suggests further work that can be done on this thesis.

In addition, to achieve a more fluent text, a nomenclature page is added in end of the thesis. Here all units of the mentioned variables and properties in the text are gathered. The terminology page in the beginning of the thesis contains a short explanation of the most important and frequent used words and abbreviations in the text.

2 Outline of the work

During the study for this thesis the work has been through many phases. This chapter will give a short description of what have been done, why, and in what order.

To get an overall understanding the first step was to make a literature study. This includes reading about gas turbines, and then further about evaporative gas turbines and the EvGT project. A deeper study of the humidification tower, or humidifier, and especially the flue gas condenser was also done. During this time I also had the opportunity to visit and see the pilot plant at LTH.

The simulation and modelling would be made with the simulation tool Dymola, so this tool had to be learned. At first, basic models and simulation runs were done, and then the work with studying the more complicated models of the EvGT-cycle could start. Sycon's ENERGY library was also studied.

Next, the humidification tower had to be validated. This demands an understanding of the variables and parameters in it. The humidifier model was studied, both graphically and the equations in all internal sub-models. The model is very complex, including many equations. The focus was laid mainly on what the equations achieve and not on how they had been derived.

Before the validation of a model could begin a verification of it had to be done. The verification of the humidifier model had been done earlier by Sycon, but with different external conditions compared to the measurement values from the pilot plant. Then one component in the EvGT cycle, the aftercooler, was not included in the cycle, which resulted in higher gas and lower water inlet temperatures. This is probably the reason why validation problems occurred. The validation can be divided into two parts, static and dynamic validation. These concepts are explained further in Chapter 2.1. The static validation was prioritised and was done first. Due to lack of time the dynamic validation had to be postponed.

When the validation of the humidification tower was finished it was time to start modelling the flue gas condenser. To do this a detailed study about the component had to be done.

Two different types of flue gas condensers have been tested in the pilot plant at LTH, a wet and a dry one. The main difference between these is that a physical wall separates the compounds water and gas in a condenser in the dry one, while the two states are mixed in the wet.

When having enough knowledge about the condenser the design of the condenser model could start. The conclusion of the study of the flue gas condensers is that the wet flue gas condenser seems to work very alike the humidification tower. The starting point is therefore the already existing and studied model of the humidifier, and the decision was

thus to model a wet flue gas condenser and not a dry one. When modelling, the desire is to reuse as many already existing sub-models from the ENERGY library as possible.

One conclusion is that the same model can be used as a humidification tower and as a condenser. The difference that defines humidification respectively condensation is the temperature of the gas and water, and the pressure. These variables are derived from measurement values from the pilot plant at LTH.

Since measurement values for the humidification tower from the pilot plant are more complete than for the condenser, the verification and validation of the created model was done on these. This means that when validated the model as a humidifier successfully, the model also will work as a condenser.

During the thesis work, the Department of Heat and Power Engineering at LTH released a report about the humidification tower. In this the calculation of the evaporation process of the humidifier is investigated. Since these calculations differed from the existing equations in the humidification tower model and the condenser model, work was laid on implementing these equations.

2.1 A note on verification and validation

The concepts verification and validation can have different meaning for different readers and in different contexts. To avoid confusion the meaning of the words in this thesis are explained below. Figure 2.1 shows the basic steps to go through when modelling.

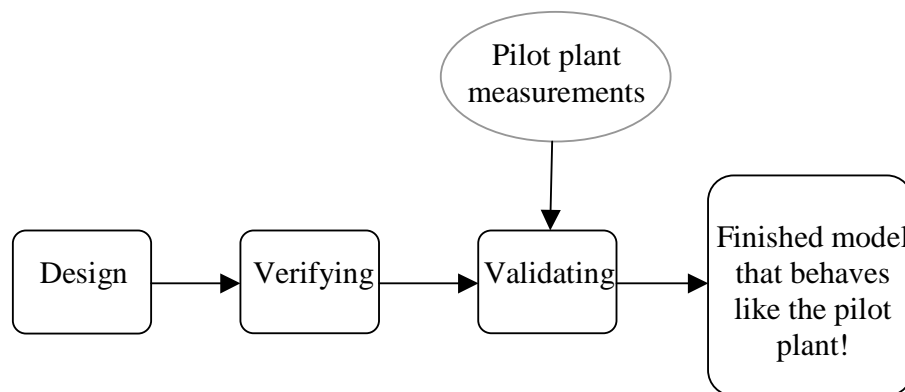


Figure 2.1: When modeling, the design of the model is needed first. Then the verification and validation can proceed, where after the model is finished.

Verification means that the parameters only are approximate ones and does not fit the pilot plant. When a succeeded verification has been done the model behaves as desired, but real measurement values have not been tested on it. The verification of the humidification tower and condenser could mean to check that the mass flows go in desired directions, the heat transfer is good enough, or the amount of evaporation is acceptable.

The validation work use real measurements to make the verified model behave like the pilot plant. As mentioned this can be divided into two parts, static and dynamic validation. It should be emphasized that the verification and validation phases are often iterative processes.

After a certain time of simulation, in this case a few seconds, the values become static, i.e. the values do not fluctuate. With access to these static values and measurement values from the pilot plant the static validation can be done. The simulated values and the ones from the pilot plant should match.

The more complicated dynamic validation means that all simulated values should be the same as the measurement values all the time, even during the initial transient. The variations of all variables should agree.

3 Evaporative Gas Turbine

This chapter describes interesting application areas for the evaporative gas turbine cycle. It also handles the pilot plant that was built at LTH and its components.

3.1 Application areas

A market and application analysis of the evaporative gas turbine cycle has been done in a master thesis (Melin and Simonsson, 2001). The conclusion of the report is that the most interesting industrial application areas are:

- Pulp- and paper industry.
For electricity, process heat, and process steam.
- Food industry.
For drying, cleaning, sterilisation and heating purposes.
- Hospitals and airports.
For electricity for lighting, and heat for heating of buildings, in combination with demand of possibility to generate their own electricity.

An investigation of competitive technologies was made to identify which power range the EvGT-cycle should operate in. The results were that the cycle should operate in the range of 3-50 MW_e.

Other interesting areas for the use of the evaporative gas turbine are for district heating production and electric production.

3.2 The pilot plant

The pilot plant at LTH was built in a small scale to identify the potential of the evaporative gas turbine cycle. It is the world's first evaporative gas turbine unit that was erected. Mainly, it consists of a 600 kW gas turbine, a water brake, a recuperator, an after cooler, a humidification tower, an economiser, and a flue gas condenser. These components will be further discussed in Chapter 3.2. In 1998 the construction was finished and testing could start.

The evaluation of the turbine showed better results than expected and involved project members agree that it has an immense potential in the future market.

The gas entering the combustion chamber consists of about 15 % water vapour after humidification. This water obstructs the founding of CO and lowers the combustion temperature from about 1400 °C to 1000 °C. However, if the load is below 50 % the CO production increases rapidly, which is not desired. The low combustion temperature keeps the NO_x emissions down. The tests of the EvGT pilot plant showed that the NO_x emissions were reduced by 90 % compared to a traditional simple cycle.

Another advantage with the evaporative method is the high thermal efficiency. Efficiency is a way to express the performance of converting energy, usually in the form of heat, to work. However, the value of the thermal efficiency of the pilot plant is about 35%, which means that 35% of the energy is converted to work. It is one of the highest values compared to combined cycles based on the same turbine. Adding the emission

advantages this would be an economical and environment friendly choice in the gas turbine market. Read more about the emissions and the efficiency of the pilot plant in (Lindquist, 1999)

The humidification of the air in the humidification tower also showed a better result than expected. The outlet gas from the humidifier was always saturated; the gas had absorbed as much water vapour as possible. The water can then be reused with a flue gas condenser, meaning that no extra water is needed.

3.3 The EvGT cycle

The pilot plant was erected according to the EvGT cycle seen in Figure 3.1 below. The figure shows the different components and the direction, which the gas and water flows. The bypass is needed for the starting phase and for safety if something unpredictable happens. Air bleed-off is used to balance the flow between the compressor and turbine, since the turbine not is constructed for evaporation. A description of the components and what they are needed for follows in this section.

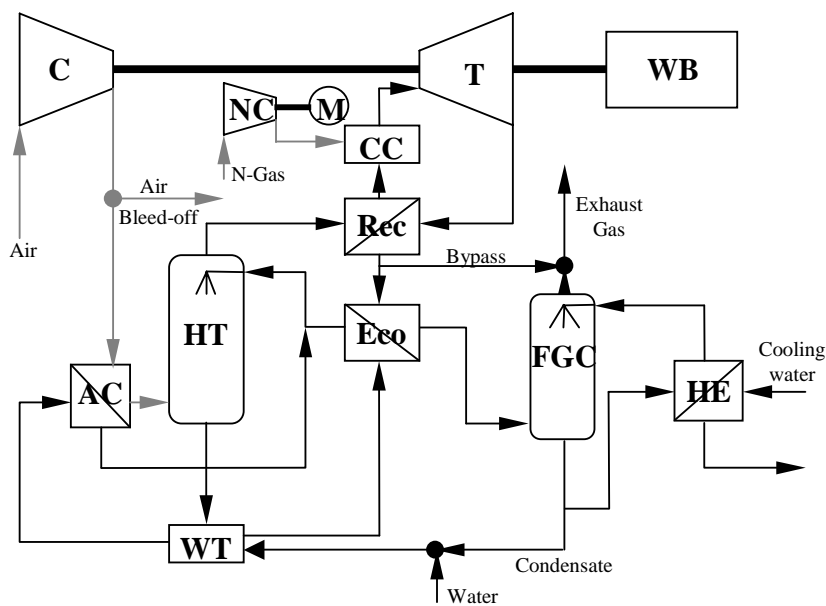


Figure 3.1: The evaporative gas turbine cycle. **AC**, **Eco**, **Rec** and **HE** represent different types of heat exchangers. Air enters the compressor **C**. In the humidification tower **HT** the air is humidified. After passing the combustion chamber **CC** it enters the turbine **T** and work is produced. The exhaust gas from the turbine passes the flue gas condenser **FGC** before leaving the cycle. The water vapour from the gas is condensed in the condenser and then led back to the humidification tower.

Turbo set

The turbo set consists of a compressor (C), a gas turbine (T), an after cooler (AC), and a combustion chamber (CC).

The compressor raises the pressure of the gas. Gas, in this case air, is led into the compressor and the result is a greatly increased pressure. What happens inside the compressor is that energy from the turbine via the shaft is transformed to an increase in pressure and enthalpy. Blades are assembled to the rotating shaft, which provides work to the compressor. When the blades are rotating they push the gas in the compressor and a raise in pressure and thus enthalpy occur.

The gas turbine absorbs energy when gas is expanding in it. During this process the pressure and temperature of the gas is decreasing. When gas enters the turbine, the blades inside it and the shaft assembled with them, begins to rotate because of the flow. The torque from the shaft can perform any mechanical work, which is mostly used to drive the compressor. The remaining torque can perform any mechanical work. In the pilot plant it is used to drive a water brake (WB) to simulate a load.

The aftercooler is a heat exchanger between the compressed air and the water coming from the humidification tower. In the aftercooler the air temperature falls when heat is exchanged with the colder water. This means that the water temperature rises. The heated water is then mixed with the water from the economiser and later led back to the humidifier. The air with lowered temperature and the water with increased temperature are then led into the humidification tower. The advantage of the aftercooler diminishes with lower gas temperature.

The combustion chamber converts the chemical energy of the fuel to an increase of enthalpy in the gas. The fuel used in the pilot plant is natural gas. The gas passes the combustion chamber just before it enters the turbine.

To be able to enter the combustion chamber the fuel used in it must have higher pressure than the gas. Therefore the natural gas is treated in a compressor to increase its pressure.

Recuperator

The recuperator (Rec) is a gas-to-gas heat exchanger where the gases not are mixed. The gases that exchange heat are the ones from the humidifier, and the exhaust gas from the turbine. To decrease the heat loss from the exhaust gas from the process, the heat can be restored to the cycle through the recuperator. With a decrease in the temperature at which heat is rejected from the cycle, the thermal efficiency of it will increase (Cengel et al., 1998).

Economiser

The economiser (Eco) is a water-to-gas heat exchanger and the purpose with it is to pre-heat the water on its way to the humidifier. Water is flowing through the volume through pipes while the gas flows outside them. The water should become as hot as possible since the heat energy is used to evaporate the water into the gas in the humidification tower.

Humidification Tower

In the humidification tower (HT) water meets gas counter-flow wise and is evaporated into the gas. The heated water from the economiser and aftercooler is flowing down through the humidification tower and some of the water is evaporated and mixed with the gas. The remaining water is brought to the water tank to get heated in the economiser or aftercooler again. The gas, coming from the compressor, is led into the bottom of the humidifier and flows upward through the tower. While flowing through the tower, water vapour is added to the gas and the gas is heated. The vapour-gas mix is then led to the recuperator.

Flue gas condenser

The flue gas condenser (FGC) recovers the water that was added to the gas in the humidifier. This will close the water loop. The flue gases containing water vapour come from the economiser and are led into the bottom of the condenser. Cooling water is sprayed from the top and makes the water vapour condense. The outputs from the condenser are exhaust gases from the top, and condensate and cooling water from the bottom.

Water from the flue gas condenser is partly reused as cooling water while the rest is fed back to the water tank. The cooling water was heated in the condenser and is cooled by a water-to-water heat exchanger (HE). This closes the water cycle in the EvGT process. The water in the heat exchanger that works as cooling medium is used for district heating.

At LTH two different flue gas condensers have been tested, a wet and a dry. Later in Chapter 6 a discussion about the differences between those and also why this master thesis handles the wet one will take place.

4 Basic structure of the models

This chapter handles the basic knowledge that is needed to model the components, especially the humidification tower and the condenser, in the EvGT cycle. It contains an explanation of the basic equations and basics about the simulation tool Dymola. The chapter is preparing for the following two chapters about the humidifier and the flue gas condenser.

4.1 Dymola

The simulation tool Dymola, Dynamic Modeling Laboratory, allows simulation of dynamic behaviour and complex interactions between, for example, mechanical, electrical, thermodynamic, hydraulic and control systems. Modelica is the object-oriented language for modelling of large and complex systems that is used in Dymola. The simulation tool includes a standard library. Sycon Energikonsult has also built its own library, ENERGY.

ENERGY

Sycon Energikonsult AB has built the ENERGY library. This library contains useful components for thermodynamic modelling like gas volumes, flows, and heat exchangers. The main feature of the library is to be able to reuse parts or sub models from different models.

The ENERGY library contains basic components that are needed in thermo dynamical processes. The library consists of nodes and connecting elements. A node represents a control volume or an open system. It describes a mass exchange with the surroundings i.e. the mass is not constant. More about the control volumes are handled in Chapter 4.2. In the nodes the state, or characteristics, of the media (steam, water, or gas) is calculated. This state is presented in a state vector, which consists of calculated elements like for example pressure, enthalpy, and density. In the connecting elements the mass and energy flows are calculated. The connecting elements can for example be valves, tubes, or turbines, which transports and/or transfers the media between the nodes.

The nodes in the ENERGY library are based on ordinary differential equations (ODE) of mass and energy conservation described in Chapter 4.2. A typical characteristic of these equations is that they are stiff, which means that there are “fast” and “slow” signals present in the solution $x(t)$. A stiff system takes long time to simulate.

There are more libraries than ENERGY in Dymola. The user is free to use components from these libraries and ENERGY when modelling. This creates a rich selection of components when creating a model, which facilitates the work.

Graphic interface

The graphic interface is especially important for a user with no experience of the Dymola tool. Looking at the graphics representing a sub model the user should be able to find out what it is representing. An explanation of some of the graphics will be done to easier understand the coming models.

The model communicates with the surroundings through cuts defined in the Dymola standard library or in Sycon's ENERGY library. Each cut defines input and output variables of the model. Both colour (red, blue, black and white etc.) and form (square, triangle etc.) of the cut symbol defines what information it represents. Figure 4.1 shows examples of the appearance of cuts.

Red represents heat transfer.
Blue represents water.
Grey/white represents gas.
Black represents common variables.
Arrow point represents output mass flow.
Arrow end represents input mass flow.



Figure 4.1: Three examples of cuts. The red one represents heat, the blue one water inlet, and the white gas outlet. Other examples of cuts are seen in figure 4.2.

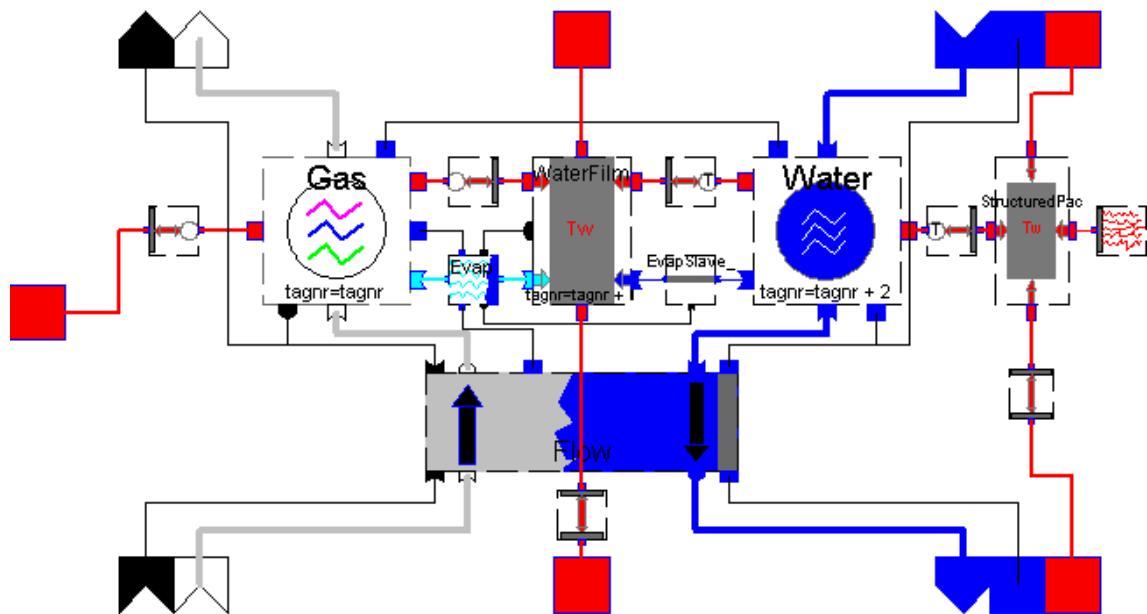
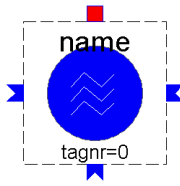
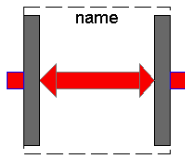


Figure 4.2: The figure shows an evaporation segment used in the humidifier. The connecting lines have different colours and the sub models have different sizes.

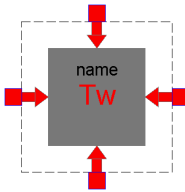
The interconnecting lines can have different colour and thickness, see Figure 4.2. Here the colours follow the same rules as for the cuts. Red represent the connection between two heat sub models, blue represents the connection between two water variables and so on. The thicker lines represent mass flow while the thinner ones represent variable or heat transfer.



A circle with waves in represents volumes or nodes. In these volumes the different states are calculated. The colour of the volume tells whether it is a water or gas volume. In the example beside the water volume has three mass flow cuts where water flows into, or out from the volume. The red square transfers heat between the node and its surroundings. The number of cuts can easy be modified in Dymola.



The heat transfer models contain a red arrow, which points in the direction of the flow. Red represents heat and the arrow shows that the heat transfer occurs in both directions. The heat transfer can be of different types like wall-to-wall, wall-to-gas, and wall-to-water. The information about the type of heat transfer is also represented by different graphics. Here the figure represents a wall-to-wall heat transfer, where the grey boards define the walls. The two red squares transfer the heat to its surroundings.



All walls contain a grey square in the centre. A wall model represents the physical wall of any kind of material, which is determined by the heat capacity. The wall contains an energy balance, which determines the temperature. In the figure the physical wall is represented by the grey square. There are four cuts, which transfer heat between the wall and its surroundings.

The graphical representation of models is possible to magnify, or reduce, to make the overall graphics easy to understand. This can be seen in Figure 4.2 above.

4.2 Basic equations

The thermodynamic property enthalpy is used in several occasions in the thesis. This property is known by H and the word enthalpy comes from the Greek word *enthalpien*, which mean *to heat*. Enthalpy is defined as:

$$H = U + P \cdot V \quad [4.1]$$

or, per unit mass,

$$h = u + P \cdot v \quad [4.2]$$

where U is the internal energy, P is the pressure and V is the volume.

As mentioned before the ENERGY library is built from the concept of a network of nodes and connecting elements (Råberg et. al, 2000). This means that the states are calculated in the nodes, while mass flows and heat transfers are calculated in the connecting elements. The nodes, or volumes, are described with ordinary differential equations, ODE, for mass and energy conservation. The conservation of mass and energy means that no mass is transformed into energy. The mass balance is:

$$\frac{dM}{dt} = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dots + \dot{m}_n \quad [4.3]$$

where $\frac{dM}{dt}$ is the net change in mass within the system and \dot{m} is the rates of mass flows into or out from it. The energy balance is:

$$\frac{dU}{dt} = \frac{dH}{dt} + \frac{dQ}{dt} - \frac{dW}{dt} \quad [4.4]$$

where $\frac{dU}{dt}$ is the change in energy forms internal energy $\left(\frac{dH}{dt}\right)$, heat $\left(\frac{dQ}{dt}\right)$, and work $\left(\frac{dW}{dt}\right)$.

Within the volumes in ENERGY library it is desired to calculate the pressure and enthalpy. Therefore the mass and energy balance has been transformed into following equations:

$$\frac{dh}{dt} = \frac{\frac{dU}{dt} - \frac{dV}{dt}(h \cdot \rho - p) - V \cdot \left(h \cdot \frac{d\rho}{dt} - \frac{dp}{dt}\right)}{\rho \cdot V} \quad [4.5]$$

The equation for the pressure is:

$$\frac{dp}{dt} = \frac{1}{\alpha_p} \cdot \left(\frac{dM}{dt} - \rho \cdot \frac{dV}{dt}\right) \cdot \frac{1}{V} - \frac{\alpha_h}{\alpha_p} \cdot \frac{dh}{dt} \quad [4.6]$$

These calculations for enthalpy and pressure are used in the volumes of the humidifier and flue gas condenser model. The units of the properties are explained in Nomenclature, page 48. Read more about the derivation of the equations in (Råberg et al, 2000).

A typical connecting element is the heat transfer. Heat can be transferred in three ways: conduction, convection, and radiation. An example of conduction is the heat transfer from warm air to a cold canned drink through the wall of the aluminum can. The conduction is:

$$Q = \lambda \cdot A \cdot (T_2 - T_1) \quad [4.7]$$

Q represents the total heat, A is the heat transfer area, and T is the temperature. The constant λ is the thermal conductivity, which is a measure of the ability of a material to conduct heat.

Convection is the mode of energy transfer between a solid surface and the adjacent gas or liquid that is in motion. This type of heat transfer involves the combined effects of conduction and fluid motion. Convection occurs for example during a change of phase of a fluid. The equation for convection in the treated models is:

$$Q = \alpha \cdot A \cdot (T_2 - T_1) \quad [4.8]$$

The heat transfer coefficient α depends on what kind of heat transfer it is. A transfer between two walls has a different α than a transfer between a wall and gas. These heat transfer coefficients can be found in tables.

Heat transfer by radiation can occur between two bodies, even when they are separated by a medium colder than the body. An example is the radiation of heat from a fire through the cold air to a person. The radiation heat transfer is calculated as:

$$Q = \varepsilon \cdot \sigma \cdot A \cdot (T_2^4 - T_1^4) \quad [4.9]$$

where ε is the emissivity and $\sigma = 5.67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$ is the Stefan-Boltzmann constant.

5 Characterizing the humidification tower

This chapter treats the features of the humidification tower. A humidification tower is used to transfer components from a liquid mixture into gas. This operation is called stripping or desorption. The humidifier is needed for connecting the liquid with the gas.

5.1 Overall description

The liquid at the pilot plant at LTH is water, which is desired to evaporate and mix with the compressed air from the compressor. The size of the tower is about 2.5 m tall with a diameter of 0.70 m. A schematic figure of it is shown in Figure 5.1. Inside the humidification tower there is packing to increase the contact area between gas and water. Water of approximately 130°C is led in on the top, and wets the structured package while flowing down. The gas of about 90°C is fed from the bottom of the tower and flows upwards. The higher it gets the higher humidity it contains due to evaporation of the hot water. While water is flowing downwards it evaporates and the goal is to have 100 % humidity in the gas when it leaves the tower. Because of the evaporation more water flows into the tower than out of it. During the process a heat exchange also will occur between the water and gas. Thus, the water temperature will decrease, and the gas temperature will increase during the evaporation process.

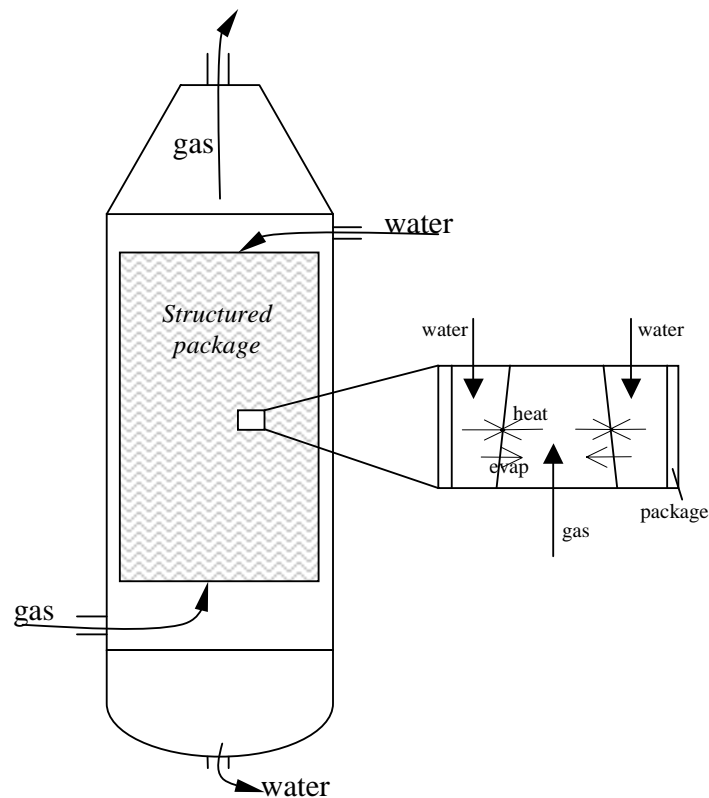


Figure 5.1: A schematic figure of the humidifier. A magnified part of the packing shows when water flows downwards along the packing while gas is flowing upwards in the remaining volume. During the process heat exchange and evaporation, i.e. mass transfer from water to gas, occur.

The evaporation in the humidifier depends on many factors. A high relative humidity makes the evaporation process slower than for a low humidity. Also, for the humidification tower, the higher water temperature and the lower gas temperature, the more water will evaporate. The contact area between gas and water determines the relative humidity of the gas. This is the ratio of the actual amount of moisture in the air at a given temperature to the maximum amount air can hold at that temperature. The relative humidity is calculated as

$$RH = \frac{P}{P_{sat}} \quad [5.1]$$

The relative humidity RH ranges from 0 for dry and 100 percent for saturated air (air that can not hold any more moisture). P is the vapour pressure and P_{sat} is the saturated pressure.

Most wet cycles inject water directly into the cycle. Since the gas turbine is sensitive to impurities the water has to have a high quality. In the EvGT cycle the water is added in the humidifier and not injected directly. Almost all soluble impurities in the water in the humidification tower will stay in the liquid phase after the humidification process. Even the small amount of soluble impurities in the gas is scrubbed out of the gas stream into the liquid, making the gas very pure. This is the reason why the humidification tower sometimes is called a scrubber. The tower's treatment of the pollutants ensures that no special effort has to be made on the purity of the gas and water.

5.2 Heat and Mass transfer

Different mass and heat transfers occur within the humidification tower. Figure 5.2 shows a schematic figure of transfers occurring in an evaporation segment.

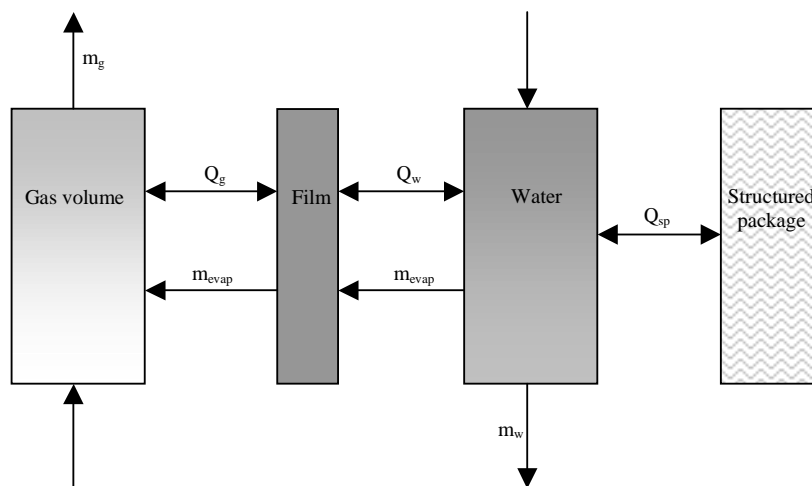


Figure 5.2: Heat and mass transfer of an evaporative segment. The structured package exchange heat with the water. The film represents the phase transition between gas and water. Between the two phases there are heat exchange, and mass transition m_{evap} from water to gas. Meanwhile the gas respective water flows in countercurrent directions, m_g and m_w .

Water and Gas flow (m_w, m_g)

Water flows from top to bottom through the package in the humidifier. The mass flow along the structured package is:

$$\dot{m}_w = c_w \cdot A_w \cdot \rho_w \quad [5.2]$$

where c_w is the water speed, A_w is the area between water and gas, and ρ_w is the water density. In a similar way the gas flow is calculated according to:

$$\dot{m}_g = c_g \cdot A_g \cdot \rho_g \quad [5.3]$$

where the subscript g refers to the gas phase. The units of the variables are found in the Nomenclature page.

Structured package heat transfer (Q_{sp})

Structured package of stainless steel is used as packing in the humidifier at LTH, see Figure 5.3. The packing tower is used to get two phases in contact to interact. In this case the interaction is between water and gas where mass transfer is desired. The larger contact area the faster interaction occurs. This is the reason why the structured package is pleated. Water wets the packing and flows like a film along it while gas passes through the remaining volume. The heat from the water affects the temperature in the structured package. All convective heat transfer is calculated as:

$$Q_{sp} = \alpha \cdot A_{sp} \cdot (T_2 - T_1) \quad [5.4]$$

where α is the heat transfer coefficient, A_{sp} is the contact area between water and package, and T_1, T_2 is the temperature of the package and water, respectively.

Water Film heat and mass transfer (m_{evap}, Q_w, Q_g)

To represent what happens when matter is transferred between two phases the two-film theory is used. The material is transferred between the phases by convection. Here, a thin layer of each phase, in this case water and gas, represent the film. The mass flow can then be calculated.

The word evaporation is used to indicate phase change from liquid to vapour. It occurs when the vapour pressure is less than the saturation pressure at a given temperature, see Figure 5.4.



Figure 5.3: The structured package in the humidifier at LTH. The packing is made of stainless steel and the parts are placed on top of each other.

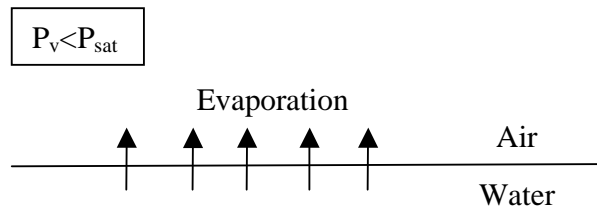


Figure 5.4: Evaporation, or phase change from water to water vapor, occurs when $P_{sat} < P_v$.

Water and air strive for phase equilibrium. The equilibrium can be expressed as the vapour pressure in the air must be equal to the saturation pressure of water at the water temperature ($P_v = P_{sat}$). Therefore, if the vapour pressure in the air is less than the saturation pressure of water at the water temperature, liquid will evaporate. The evaporation will have a cooling effect on water.

A typical example of the evaporation process is the drying of a wet T-shirt. If the T-shirt is hanging in an open area it eventually dries. This is due to evaporation. The wet T-shirt would dry much faster in dry air than it would in humid air. In fact, it will not dry at all if the relative humidity of the environment is 100 percent and thus the air is saturated ($P_v = P_{sat}$).

In the humidifier model there is a mass transfer from water to gas when evaporating, which makes the water mass decrease while flowing down. This also means that the gas mass increases while flowing upwards. The rate of mass transfer between the phases is:

$$\dot{m}_{evap} = \frac{h_d \cdot A \cdot M_w}{R \cdot T} \cdot (P_{film,H_2O} - P_{g,H_2O}) \quad [5.5]$$

where A represents the transfer area, M_w is the molecular weight of water (18.016 kg/kmol), T is the temperature of the water film, R is the gas constant (8.314 kJ/(kmol*K)), P is the pressure, and h_d is the mass transfer coefficient. The coefficient h_d depends on the film thickness where a large thickness means a bigger h_d .

Since there is a temperature difference between the water and gas the heat transfer must be calculated between those phases. According to the film theory the heat transfer is divided into two parts, one between water and film, and one between film and gas. The rate of transfer of heat can be calculated as:

$$Q_w = \alpha_w \cdot A \cdot (T_{water} - T_{film}) \quad [5.6]$$

respectively $Q_g = \alpha_g \cdot A \cdot (T_{film} - T_{gas}) \quad [5.7]$

where α is the heat transfer coefficient, A is the heat transfer area, and T is the temperature of the phases.

5.3 The humidification tower model

The model of the humidifier is built from the ENERGY library and consists of several layers. The top layer in Dymola, see Figure 5.5, is the one the user sees when simulating. In this layer it is possible to state the dimensions and physical parameters of the tower, as well as its initial states. When looking at the next layer the basic construction of the humidification tower is seen. It basically consists of several evaporation segments, the outer mantle and the connection between these. The model is seen in Figure 5.6.

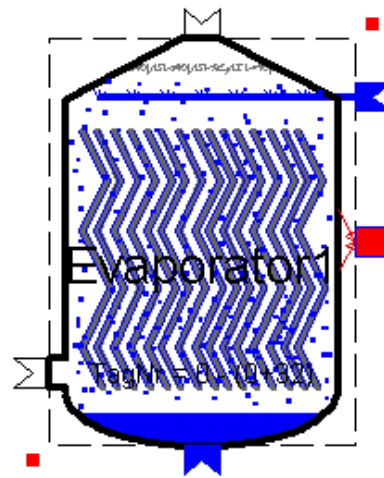


Figure 5.5: The top layer of the humidification tower in Dymola. This is the complete humidifier and is used when connecting it with other components. A double click on the figure will make it possible to determine the size and initial states of it.

When the tower was modelled by Sycon Energikonsult AB the structured package was divided into several segments. These segments calculate the mass and heat transfer from segment to segment. The number of segments should be infinite to find the correct transfer parameters. To simplify there are ten segments, which will satisfy the demands of precision.

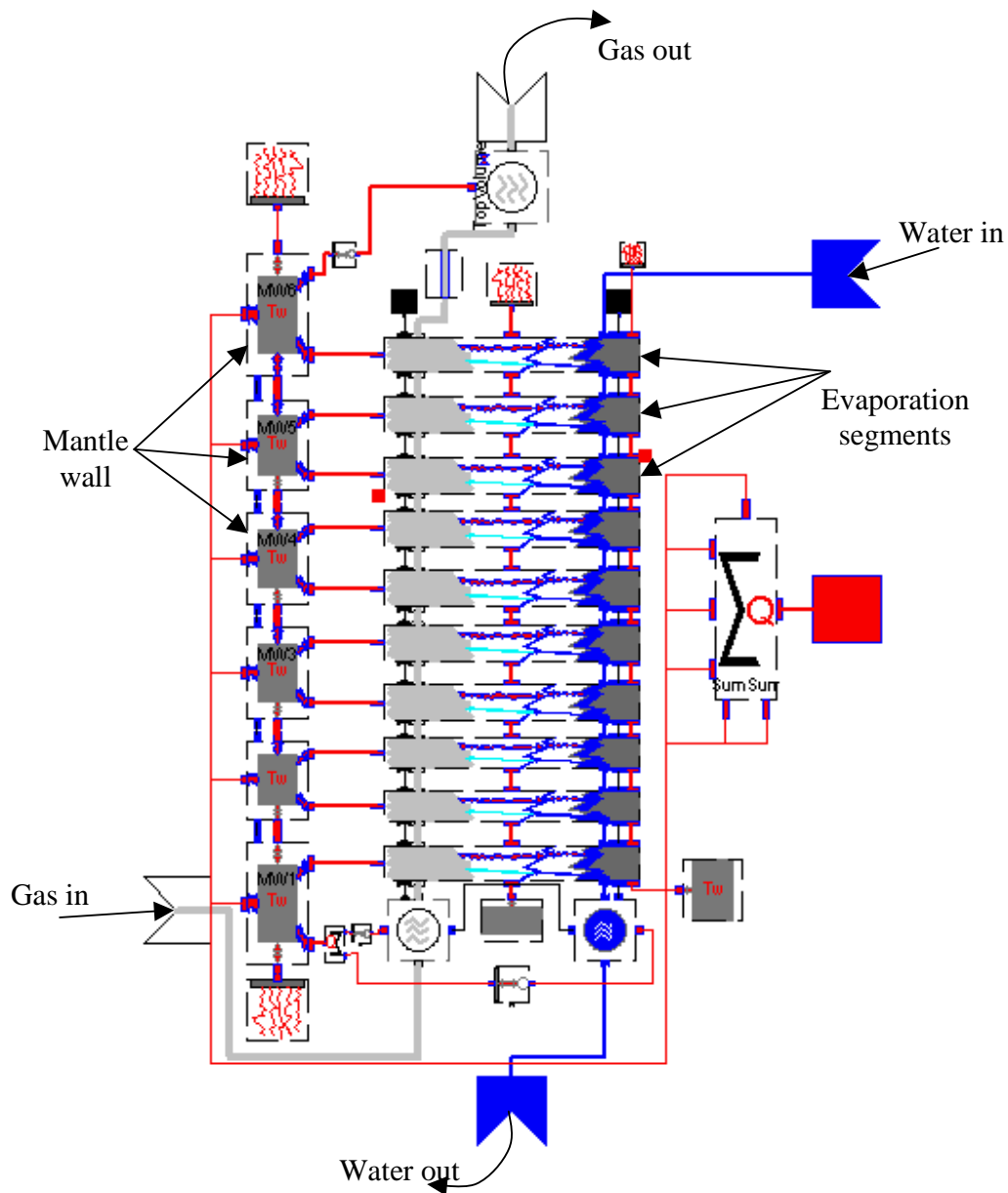


Figure 5.6: The figure shows the detailed humidifier model. The ten evaporation segments represent gas and water flow and the evaporation between the phases. The six components to the left represent the mantle wall which exchange heat with the outer air, the red square, and the evaporation segments. The white and blue cuts, which also are found in Figure 5.5, represent in and out flow of gas respective water.

The humidifier container, or the mantle wall, calculates the influence of the outside temperature, and of the evaporation segments. The wall affects the dynamics of the model. **MW1 – MW6** in Figure 5.6 represents the mantle wall with the temperatures as states. The total mantle is calculated with six wall segments exchanging heat with the surroundings.

The evaporation segment model

The evaporation segments calculate the mass- and heat transfer between gas and water when the evaporation process takes place. The segment showed in Figure 5.7 is built according to how it looks in reality and can be directly mapped to the physical model in Figure 5.2.

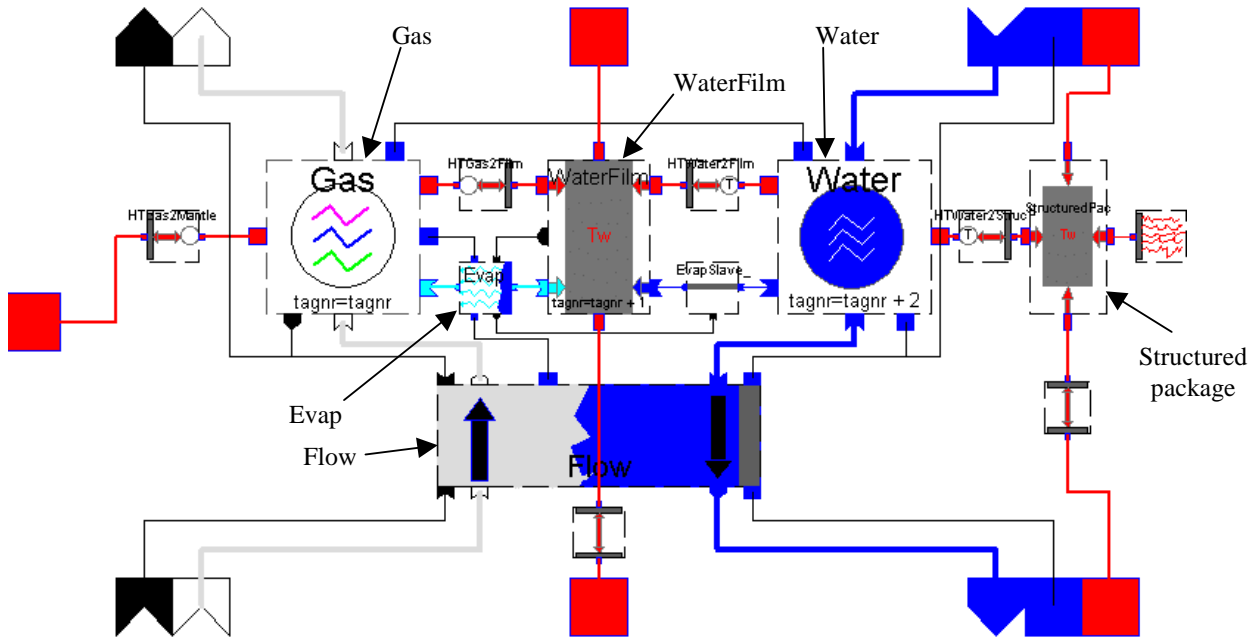


Figure 5.7: One evaporation segment. The **Structured package** to the right exchange heat with the **Water** volume. The **WaterFilm** represents the phase transition between **Gas** and **Water**. Between the two phases there are heat exchange and mass transition, **Evap**, from water to gas. The gas and water flows in countercurrent directions, where the mass flows are calculated in **Flow**.

The segment model consists of several sub models.

- **HTGas2Mantle**. This model contains gas-to-mantle heat transfer calculations.
- **Gas**. The model of a gas volume represents pressure, temperature, and composition of the gas. Since water is evaporated into the gas, the gas composition is changes for each segment. The gas mixtures are treated as ideal gases.
- **HTGas2Film**. Calculates the heat transfer between the gas volume and the water film.
- **Evap**. Represents the mass transfer of evaporated water from the water volume to gas volume.
- **WaterFilm**. The border between water and gas. The mass of the water volume is fixed and it has the same pressure as the gas and water volume.
- **HTWater2Film**. Calculates the heat transfer between the water volume and the water film.
- **EvapSlave**. This model has the same mass flow as calculated in the model Evap.

- **Water.** Represents the water film on the surface of the structured package. It has the same pressure as the gas volume and calculates enthalpy and mass.
- **HTWater2StrucP.** Calculates the heat transfer between the water volume and the structured packages.
- **StructuredPackages.** This is a model of the structured package. The temperature of the package is calculated.
- **HeatW2Fix.** The model calculates the heat transfer with a constant heat.
- **HTStructP2StrucP.** Calculates the heat transfer between the structured packages in the segment and the structured packages in the segment below.
- **Flow.** Calculates gas and mass flow. The flows are dependent on gravity, pressure, the friction between gas and water, and the friction between water and walls.
- **HTFilm2Film.** The model calculates the heat transfer between the water film in the segment and the water film in the segment below.

For the equations used in the sub-models Gas, Evap, and Flow, see Appendix A.

5.4 Static validation of the humidification tower

As mentioned the humidifier model was created earlier in the EvGT project. The model was verified, but not validated on the measurements from LTH pilot plant. The verification means that the parameters only are approximate ones. In other words, the model works as desired from a qualitative point of view and the basic functionality has been checked. Real measurement values have not been tested on it though. The validation will make the model fit real measurements.

The validation can be divided into the following steps of work:

1. Create a test bench.
2. Insert measurement values from the pilot plant at LTH.
3. Simulate until static values are reached.
4. Validate.

1. Create a test bench

When creating the test bench, Figure 5.8, the purpose is to be able to insert the measurement values from LTH in an easy way. The values from the pilot plant are mass transfer, pressure, temperature, and enthalpy for the inlets and outlets of the tower. By implementing the two sub-models to the inlet and outlet cuts, the measurements can be inserted.

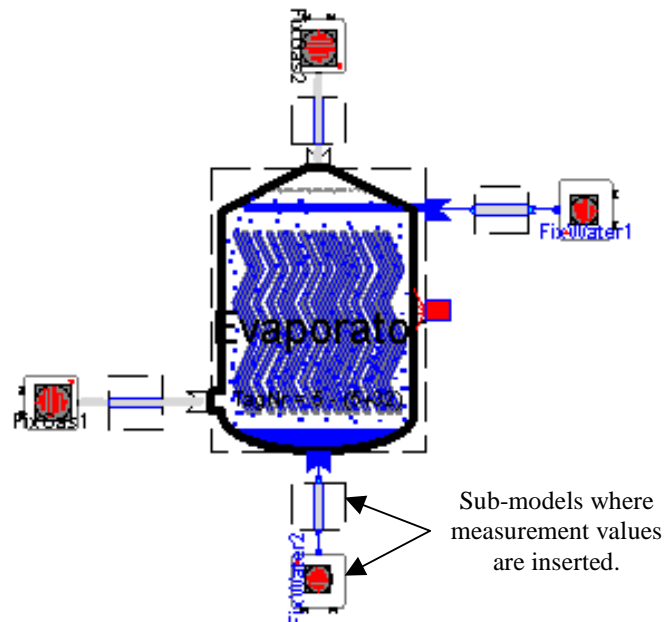


Figure 5.8: The test bench used when validating.

2. Insert measurement values from the pilot plant at LTH

Static values from the pilot plant at LTH have been measured for different loads, 40%, 50%, 60%, and 70%. Full load is 600 kW. The values below are from 70% load.

	mass flow [kg/s]	pressure [bar]	temperature [°C]	enthalpy [kJ/kg]
water inlet	6.043	9.365	128.62	540.9
water outlet	5.635	8.365	88.25	370.21
gas inlet	2.179	8.365	88.07	89.211
gas outlet	2.586	8.331	117.24	unknown

The measurement values are inserted to the test bench in the sub-models. The same values are desired in the humidifier model after simulations.

The humidification model has initial values that have to be set. For example, the temperature of all water volumes in the evaporation segments has to be set. This is done by an approximation of the desired inlet and outlet water temperature values from the pilot plant. Since the temperature is higher in the inlet, the upper segments will have a higher temperature than the lower ones. Other examples of values that have to be initiated are mantle wall temperature, gas pressure, and gas temperature.

3. Simulate until static values are reached

When starting the simulation of the test bench model the states in the humidification tower model are changed, while the measurement values in the inlets and outlets are the same as stated. After a while the humidifier reaches equilibrium and all values are static.

Eventually the initial values in the humidification tower can be set to the static values from the simulation. The simulation would then reach its equilibrium faster, since the initial values are closer to the static.

4. Validate

The static validation involves checking whether the values reached during a simulation of the humidifier model match with the ones from the pilot plant. This can be done when looking at the values in respective volume that is connected to the inlets and outlets. For example, see Figure 5.9, the outlet water mass flow should be 5.635 kg/s. This is stated in outlet of the water. The same mass flow, m_1 , is transported from the volume. When simulating, the value of the calculated mass flow, m_2 , from the lowest evaporation segment is transported to the volume. If the two mass flows m_1 and m_2 differ, the volume will either decrease or increase, depending on which flow is the largest. m_1 is the desired value, and the validation includes checking whether the final static m_2 differs from it.

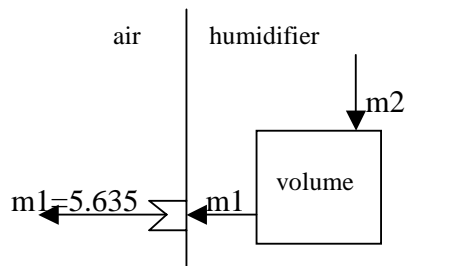


Figure 5.9: The validation includes matching the values m_1 and m_2 .

The validation of all measurement values is done in a similar way as for the mass flow.

The validation of 70% load showed a too high mass flow of the water outlet, see Figure B.2 in Appendix B. To decrease the water mass flow more evaporation of the water in the humidification tower is desired. The amount of liquid water would then decrease and thereby the outlet mass flow.

The validation also shows that the gas pressure in the tower is sinking from the desired value 8.365 bar. The pressure in a volume is calculated from the sum of mass and energy that is transported into it according to mass balance. It is thereby desired to transport more mass and energy to the gas volume. This can be done through a higher evaporation, which means that more mass will be transferred into the gas. To increase the energy the heat transfer between the gas and water film, and water film and water, should be higher.

The equation for mass flow is shown in equation A.4 in Appendix A. It is found that it depends on several parameters, which are not exactly determined. Therefore, the validation includes setting the parameters so that they match with the humidification tower model.

Two of the parameters are the heat transfer coefficients α_w and α_g , which affect the temperature calculation used in the mass flow calculation. A higher α -value gives a higher heat transfer, and thereby a higher temperature in the gas volumes. Since the α_g -value between gas and water film earlier has been determined to be 0.13 this value was not desired to change. Instead α_w was.

Another variable that affects the evaporation calculation is the mass transfer coefficient, here called ce . The coefficient depends on two parameters, a and b , see equation A.5 in Appendix A. Even these parameters were changed to achieve a little improvement of the mass flow value.

The surface roughness parameter $rugwg$ between water and gas is used when calculating the friction force Fm between the two phases. The force Fm is used in the calculation for the speed of the gas and water. When raising the parameter $rugwg$ the speed is decreasing and thereby the evaporation should increase.

When changing most of the parameters too much the model got stiff. Figure B.3 in Appendix B shows the best result of the simulation after changing parameter values. It shows that the mass flow still does not reach the desired value. Even the pressure still is sinking.

5.5 Analysis/Evaluation

A problem when simulating is the slowness of the model simulation, because of its complexity. Thereby it has been difficult to experiment with the parameter values. A simulation of 20 seconds in real time is necessary to see the final static values. This takes 8-10 hours on the computer. A small oscillation of the static values is probably the reason of the long simulation time, since they probably cause a stiff behaviour. The reason of

these oscillations is probably caused by a loop in the calculations. This loop does not exist in the condenser model described in Chapter 6, where the difference in simulation time will be discussed.

Validating the humidifier showed to be more difficult than expected. When finding out after the first simulation that the evaporation should be higher, the problem seemed to be able to solve. When raising the parameters too much the model became stiff. After having looked at all possible parameters the problem still remains, the energy transfer between gas and water is too low.

Many different parameters affect the evaporation process. These are the heat transfer coefficient between water and water film, and water film and gas. Other parameters that affect are the surface roughness and the mass transfer coefficient.

One of the reasons why the validation of the humidifier was difficult could be that the heat transfer coefficient α_w was proposed to have a value about 0.13. Therefore no large change of this parameter was done. This value has later on showed to be far from the real value that probably is about 4.6 and will be used in the condenser model in Chapter 6.

Another reason why the validation did not go as expected could be that the verification was done with values assuming that no aftercooler was a part of the EvGT model. The aftercooler cools the gas and heats the water before the components are entering the humidification tower. This means that the inlet temperatures both of the water and gas are different when the aftercooler is included from when it is not.

6 Flue gas condenser

Chapter six treats the features of the flue gas condenser. A condenser is used to transform water vapour into liquid. The flue gas condenser resembles the humidification tower in many ways and these similarities also are studied. When the basics about the condenser have been covered, the modelling work is explained.

6.1 Condensation

Condensation is the phenomenon when vapour is transformed into water because of a cooling effect. The process for atmospheric pressure, 101.325 kPa, is shown in Figure 6.1. Vapour with a temperature over 100 °C is called superheated (5). This means that it is not about to condense. If a heat loss occurs the temperature drops to 100 °C and the vapour is now on its way to condense. The vapour is now called saturated (4). The condensation occurs during constant temperature, called an adiabatic process (3). Right after the condensation, while the water still is 100 °C, the water is called saturated (2). Small added heat would cause evaporation. If the temperature keeps sinking, the water is called sub cooled (1).

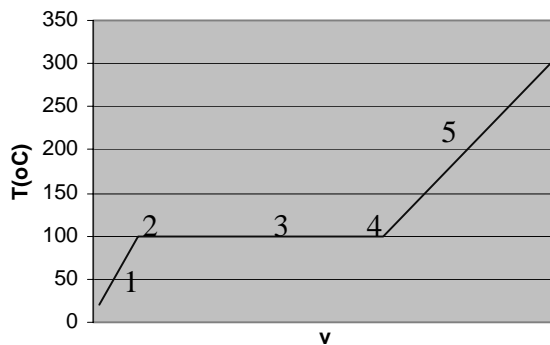


Figure 6.1: The condensation process for atmospheric pressure. Here the temperature is shown as a function of the volume of liquid and/or vapour.

At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature T_{sat} . Likewise, at a given temperature, the pressure at which a pure substance changes phase is called saturation pressure P_{sat} . In Figure 6.1 T_{sat} is 100°C at the pressure 101.325 kPa. If the pressure were raised to 500 kPa, the condensation would start at $T_{sat}=151.9^{\circ}\text{C}$. This would mean that the complete curve in the figure would move upwards. During a phase-change process, pressure and temperature are obviously dependent properties, and the relation between them is:

$$T_{sat} = f(P_{sat}) \quad [6.1]$$

6.2 Wet or dry condenser?

As mentioned in Chapter 1.1 two different flue gas condensers have been tested in the pilot plant, a wet and a dry one.

The dry one looks like a box. Inside the box there are tubes with cooling water. The flue gas flows through the box and the cooling water makes the gas condense. The condensation process makes drops of water arise on the flanges, whose main purpose is to increase the transfer area. The condensate then flows down to a collecting vessel, after which it is led back to the water tank.

The wet flue gas condenser has some basic differences from the dry one. The most significant one is that water and gas are mixed without any walls between, thus the word 'wet'. It looks like a pipe, which is filled with some kind of packing material. The cooling water is sprayed into the tower from the top and the gas is led into it from the bottom. Since no walls separate the gas and cooling water, the resulting condensate will be mixed with the water. When the water has exited the tower, the same amount of water that entered the tower goes to a cooler, while the rest of the condensate is led back to a water tank.

The use of the two mentioned types of flue gas condensers is widely spread, and none of them has been recognised as more effective than the other. The advantage of the wet one is that it can be built from less costly material like plastic. The dry one should be built of stainless steel, which is an expensive material, to keep it from corroding. When the pilot plant was erected copper was used instead, which caused a high copper concentration in the water condensate and destroyed the condenser.

The wet flue gas condenser resembles the humidifier in many ways, which will be further discussed in Chapter 6.3. This similarity is the biggest reason why the modelling will be done with the humidifier model as a starting point. Another reason is the accessibility of measurement values, which are better for the wet one. Even the cost aspect gives the wet flue gas condenser an advantage.

6.3 Characteristics of the flue gas condenser

A condenser is used to condense the water vapour in a gas. The cooling water in the condenser cools the gas, which causes a phase transformation of the water from vapour to liquid. At the pilot plant at LTH a small condenser tower has been erected. The size of the tower is about 2.5 m tall with a diameter of 0.15 m. A schematic figure of it is seen in Figure 6.2. As in the humidification tower there is a filling material in the condenser. It is made of plastic and occupies 2 m of the complete height. The function of the packing is to increase the area between gas and water. The condenser works similar to the humidifier. Water is sprayed on the top of the package while the exhaust gas is led in from the base. The water flows downward along the packing and the gas flows upward through the rest of the volume. The hot inlet gas of approximately 100°C consists partly of water vapour. When it is brought into contact with the colder water of about 30°C the water vapour condenses. The water flowing through the condenser is collected in the base. This water is a mix of both cooling water and the produced condensate. A fixed

amount of water is pumped out of the condenser to be reused as cooling water. The rest of the water is brought back to the water tank after passing a treatment process in the cycle, to be reused in the humidifier.

The treatment process consists of different components. An ion exchanger will achieve higher purity. Before the ion exchange a CO₂-stripper will remove eventual carbon dioxide and a particle filter will remove dust.

To produce a sufficient amount of condensate the exhaust gas has to be cooled down to a certain temperature. In a doctoral thesis (Ågren, 2000) this issue was studied and the conclusion was that the flue gases in the pilot plant should be cooled down to 35°C. The amount of condensate will then make the cycle self-supporting with water.

The hot exhaust gas flowing through the condenser heats the cooling water used in it. To be able to reuse the water it has to be cooled down in a heat exchanger. The water is approximately 40°C when leaving the condenser, which means that it has to be cooled down about 10°C to reach the desired inlet temperature. It would have been possible to skip the water cooler and let the water in through a tap and pump out the same amount. The advantage with the water cooler is that the water use is less if just cooling the already used water down. Further, the water in the heat exchanger that works as cooling medium is used for district heating.

Packing

The packing in the condenser at LTH consists of plastic pall rings, see Figure 6.3. These are put in a random way in the tower. The purpose is to increase the contact area between exhaust gas and water. This will boost the condensation process since it occurs when gas is in contact with water.

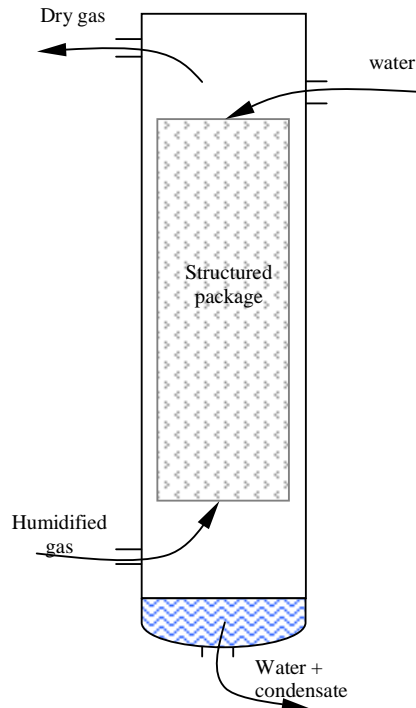


Figure 6.2: A schematic figure of the condenser. The water flows downwards and the gas flows upwards between the packing. During the process heat exchange and condensing i.e. mass transfer from gas to water, occur. The condensate and water is collected in the bottom of the condenser.

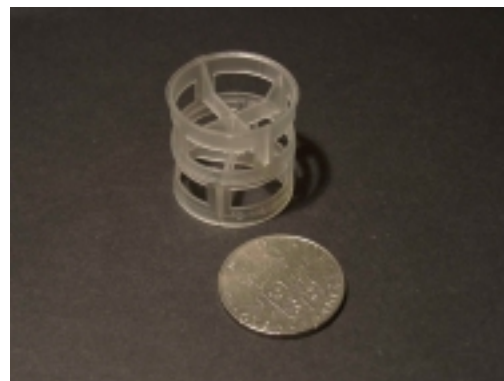


Figure 6.3: The packing of the condenser. The purpose of the coin is to show the size of the plastic pall ring.

Mantle wall

The condenser container, or mantle wall, of the condenser is in contact and exchanges heat with the outside air and the inside water. The wall is made of plastic.

6.4 Ideas about the condenser model

The real pilot plant in combination with the modelled humidification tower is the starting point when modelling the condenser. The goal is to reuse as many sub-models from the humidifier as possible.

The outermost model will have five cuts to communicate with the surrounding, see Figure 6.4. These are gas in, gas out, water in, water out, and heat transfer between mantle and air.

The physical size of the flue gas condenser should be modelled in a similar way as for the humidifier model. Walls from the ENERGY library will be used where for example height, diameter, thickness, and density are parameters, which can be specified.

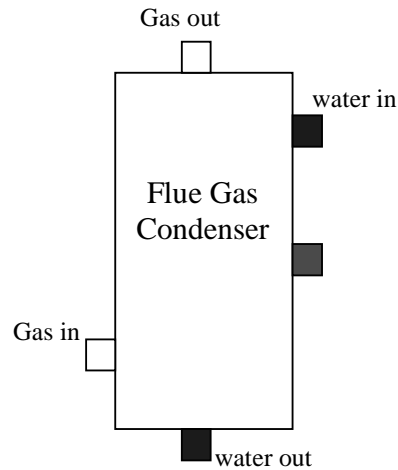


Figure 6.4: The outermost model of the condenser. The connection to the surroundings is the in and out flows of gas and water, and heat exchange between the mantle and the outer air.

In the humidifier the assumption is made that no water flows along the container, and the mantle wall then is modelled with a heat exchange with the gas, as seen in Figure 6.5. This assumption does not agree with reality since water in the condenser at the pilot plant flows along the packing but also along the mantle of the condenser. Therefore the heat transfer in the condenser model is corrected with a transfer partly between mantle and water volume, partly between packing and water volume, shown in Figure 6.6.

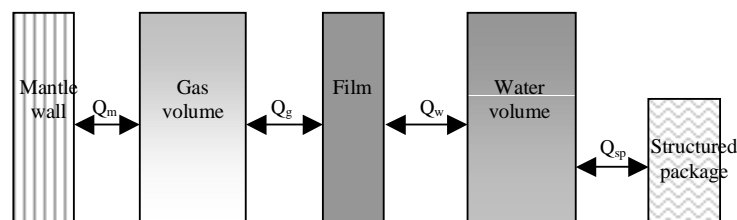


Figure 6.5: Heat exchange in the humidifier. The gas and water will exchange heat, Q_g and Q_w , with the phase transition segment Film between. The structured package exchange heat, Q_{sp} , with the water while the mantle wall exchange heat, Q_m , with the gas.

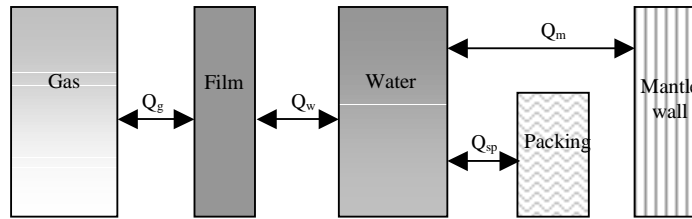


Figure 6.6: Heat exchange in the condenser. The gas and water will exchange heat, Q_g and Q_w , with the phase transition segment Film between. Both packing and mantle is in contact with the water and heat exchange between these, Q_{sp} and Q_m will occur.

A reason why the simulation of the humidification tower is slow could be that many pressure derivative calculations are done for every segment. Therefore, instead of splitting the gas and water up into the same number of segments, the gas is represented by two volumes and the water by ten as before. The derivative calculations will then be fewer. There are more derivative calculations in the gas volumes than in the water. Besides, the temperature of the water is strongly bounded to the water film temperature, whose temperature profile is needed. Therefore it is desired to divide the water into more segments than the gas.

6.5 Modelling the condenser

After deciding that the ten gas volumes in the evaporation segments of the humidification tower should be summarised and represented by only two volumes the modelling work could start. The outermost model, Figure 6.7, will look exactly like the humidification tower. As for the humidifier the five cuts represent gas in and out, water in and out and heat. It is possible to specify properties like physical size and all initial values.

A more detailed view with all sub-models of the condenser is shown in Figure 6.8. It is quite similar to the humidification tower model. The ten evaporation segments still exist but with some changes. The segments contain the same water components and the mass transition calculations while the gas volume has been removed. The mantle walls have been placed on the right hand of the model to make the graphics easier to follow.

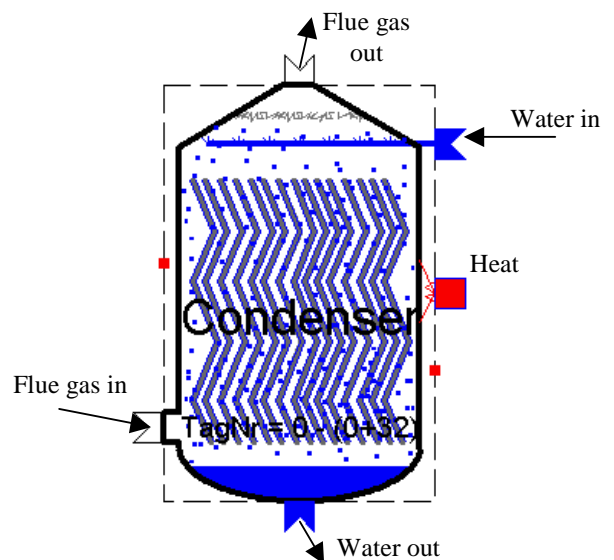


Figure 6.7: The top layer of the condenser in Dymola. This model is used to connect it with other models.

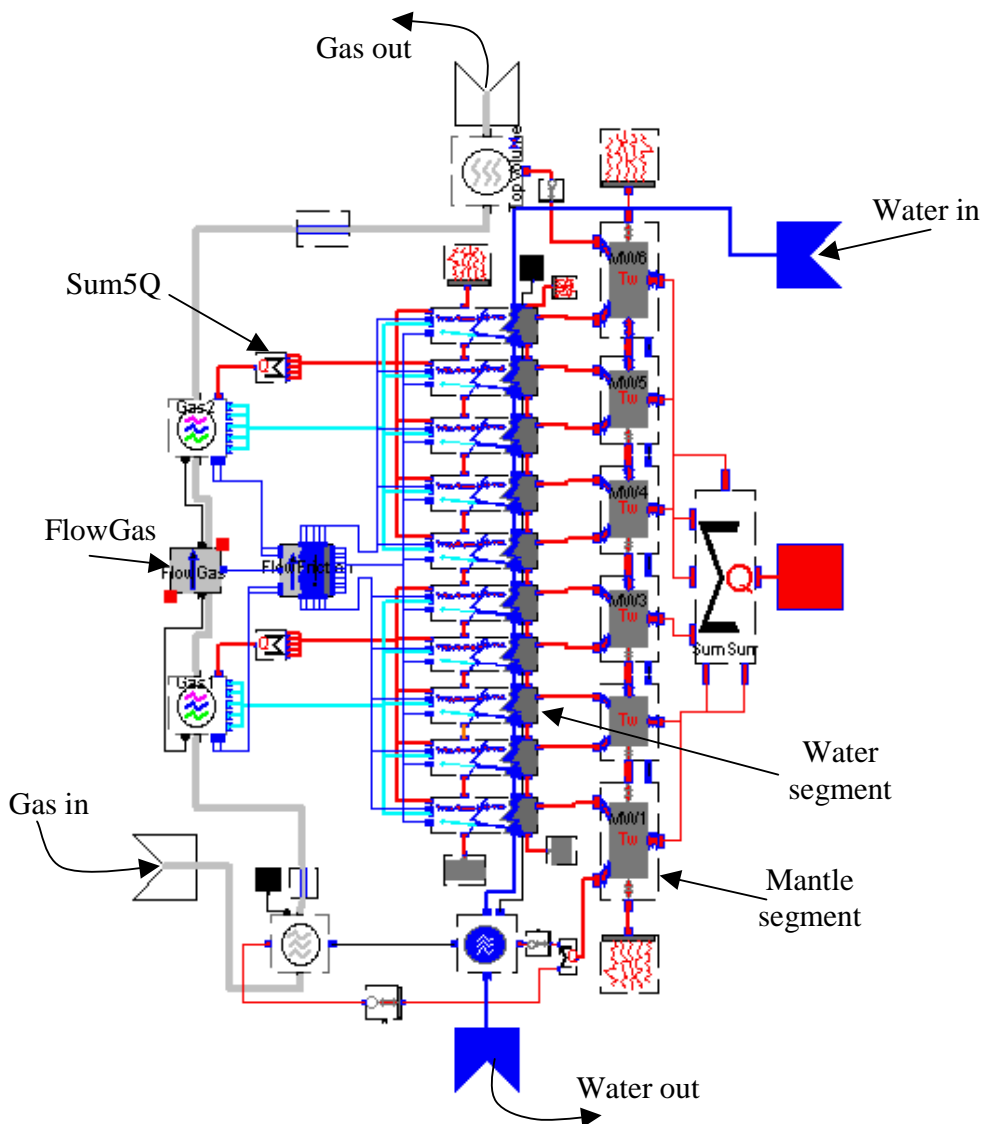


Figure 6.8: A detailed figure of the condenser model. The ten similar water segments represent the water flow and condensation process. To the right of them the six mantle segments representing the mantle wall are seen. The model **FlowGas** calculates the gas mass flow between the two gas volumes **Gas1** and **Gas2**.

The water mass flow has to be calculated in all ten segments, while the gas mass flow only needs one calculation; the one between the gas volumes. The humidification tower contains the model **Flow**, called **FlowFall** in Figure 5.7, which calculates mass flow for both gas and water, and the friction forces between the mediums. This **Flow** model is divided up into three different models in the condenser model; one for mass flow, one for gas flow, and one for the interaction between the volumes. The gas volume has been moved out from the segment, bringing the gas flow model, **FlowGas**, and the interaction

model, Friction, with it. The water flow, FlowWater, will still be calculated within the segment.

The heat exchange between the gas and the water film is treated in a model that summarizes the heat from the five lower respectively upper water segments and passes the result to the respective gas volume.

Created sub-models

The FlowFall model has been replaced by three models, see Figure 6.9.

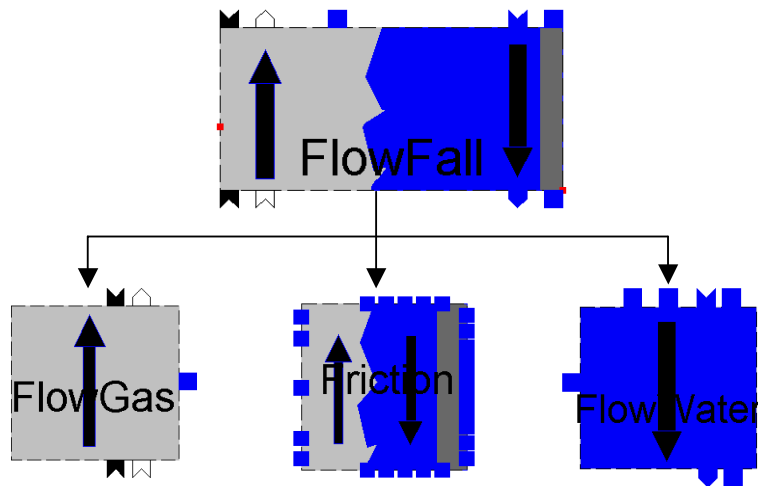


Figure 6.9: The figure shows the model FlowFall used in the humidification tower and how it has been divided into three models, FlowGas, Friction and FlowWater. These three new models are used in the condenser model.

FlowWater. This component calculates the mass flow of the water. The calculation is based on the friction forces between gas and water, which are calculated in FlowFriction.

FlowGas. This component calculates the mass flow of the gas. The calculation is done based on the friction forces between gas and water, which are calculated in FlowFriction.

Friction. This component calculates the friction forces between gas and water, and then passes them to FlowGas and FlowWater.

The total volume of the condenser has been divided into two equally big gas volumes, while the water is divided into ten volumes. Thus, one gas volume corresponds to five water volumes. In the model Friction variables are divided up or summarized. Four different variables are calculated; the friction forces for gas and for water, the gas pressure, and the vapour pressure.

The water mass flow should be calculated with ten different friction forces, while the gas mass flow only needs two. This is done by taking the mean value of the five upper respectively lower segment's friction forces.

The five upper water volumes will have the same pressure and pressure derivative as the upper gas volume. These calculations are made in the gas volume and passed on to the water volume. The same goes for the five lower water volumes. When evaluating the pressure change in the ten segments of the humidifier model it was found out that the intervals is of even distance between every segment. Plots are shown in Appendix C in Figure C.1 and C.2. This gives that the pressure should be increased with the same amount for every water volume. If the pressure at the bottom of the condenser is p_{in} and p_{out} at the top, then the pressure p for each water volume is calculated by:

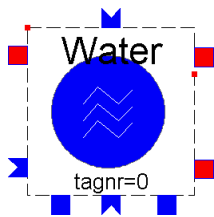
$$\begin{aligned}
 p1 &= p_{in} \\
 p2 &= p1 + (p_{out} - p_{in}) / (NOS - 1) \\
 p3 &= p2 + (p_{out} - p_{in}) / (NOS - 1) \\
 p4 &= \dots\dots\dots
 \end{aligned}
 \tag{6.2}$$

where NOS is the total number of water volumes.

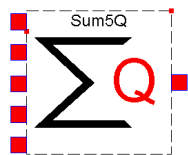
In Figure C.1 and C.2 in Appendix C the pressure change over time, i.e. the pressure derivative, is equal. This gives the conclusion that the pressure derivative is constant. In case the derivative varies it will be divided in even distances in the water segments.

The vapour pressure used in the mass transition model Evap is calculated in the gas volume, which corresponds to five water segments. When evaluating the pressures the distances between the segments are equal, see Figure C.5 and C.6 in Appendix C. This gives that the vapour pressure should be increased with the same amount for every segment.

Small changes on existing models have resulted in new ones:



Water. As mentioned earlier the heat transfer occurs between the water and mantle wall, instead of the gas and wall, which results in a modification of the water model. The mass transition will be calculated in same way as for the evaporation in the humidifier. The volume has three water flow cuts, two cuts for transport of variables, and three cuts for heat transfer with the surroundings.



Sum5Q. To summarise the heat from the ten water segments a model with six cuts was created. The five upper water segments will exchange heat with the upper gas volume through this model, see Figure 6.8. The five cuts on the left of the figure represent the heat exchange with the five segments, and the one on the right exchanges heat with the gas

volume.

Evaporation segment

The evaporation segment is showed in Figure 6.10 below. The big difference from the corresponding segment in the humidifier is that the gas volume has been eliminated and thereby the former model FlowFall is replaced by FlowWater.

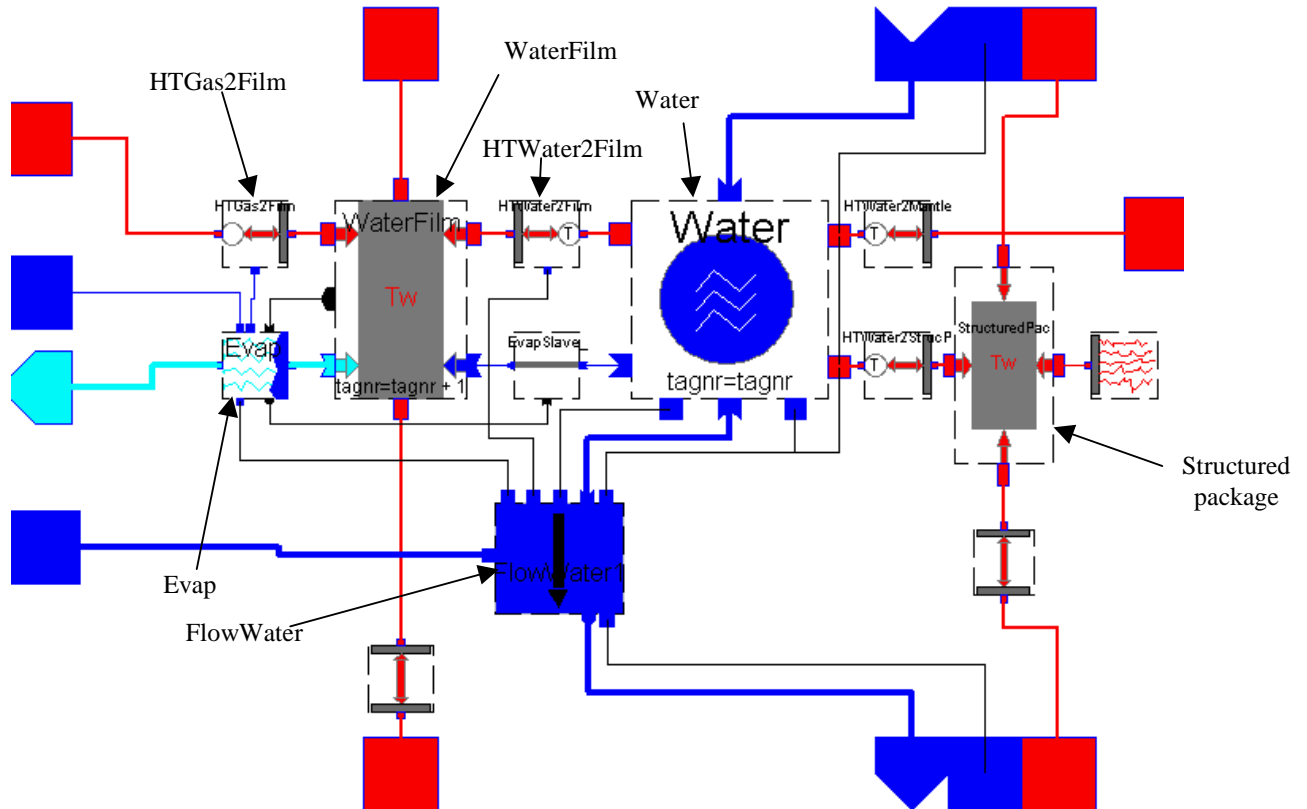


Figure 6.10: A water segment in the condenser. The **Structured package** to the right exchange heat with the **Water** volume. The **WaterFilm** represents the phase transition between gas and **Water**. Between the two phases there are heat exchange and mass transition, **Evap**. The gas and water flows in counter current directions, where the water mass flow is calculated in **FlowWater**.

New mass transfer calculation

Using the same model for evaporation as used in the humidifier model yields unsatisfying results. It seemed difficult to get enough water to evaporate. The Department of Heat and Power Engineering at LTH recently published a report on how to calculate the evaporation (Lindquist et al, 2002). These new equations were implemented in the model. A mass transfer coefficient h_d is introduced, which replaces the three unknown parameters a , b , and α_g in equations A.5 in Appendix A, and 5.7.

The new calculation of the mass flow is:

$$\dot{m}_{evap} = \rho \cdot h_d \cdot \frac{\omega_f - \omega_g}{1 - \omega_f} \cdot A_f \quad [6.3]$$

where ρ is the density, h_d is the mass transfer coefficient, A_f is the area between gas and water, and ω_f , ω_g is the humidity ratio of water in the water film and gas volume, respectively.

The equation for the heat transfer coefficient used in equation 5.7 is:

$$\alpha_g = \rho \cdot h_d \cdot c_p \cdot \left(\frac{D_{ab} \cdot \rho \cdot c_p}{\lambda} \right)^{-s} \quad [6.4]$$

where c_p is the specific heat capacity, D_{ab} is the diffusion coefficient, and λ is the thermal conductivity. The exponent s normally is 2/3, but can vary between 0.5 and 0.75 (Lindquist et. al, 2002). The value of the parameter h_d depends of whether it is condensation or evaporation, and temperatures and pressures of the model.

Diffusion is a critical property in the evaporation and condensation processes. Diffusion is the ability for a substance to spread into other. A well-known example is sugar that diffunds in a cup of coffee until the cup has the same amount of sweet in the whole cup. In the case of evaporation it is water that diffunds into gas. The uncertainty for the diffusion coefficient D_{ab} is very high due to lack of experimental data. This could cause differences from desired values during a simulation run.

The heat transfer coefficient α_w between water film and water was in the humidifier model independent of the thermal conductivity λ and the thickness of the water film t_w . It is, however, physically dependent of these two properties and the equation for the coefficient is now implemented as:

$$\alpha_w = \frac{\lambda_w}{t_w} \quad [6.5]$$

The modifications due to the diffusion resulted in small changes in three of the sub-models in the water segment, see figure 6.11. The only difference is the implementation of the equations 6.3 – 6.5 and new cuts which make it possible to send and receive variables that are needed. HeatN2WConv represents the model HTGas2Film in Figure 6.10, and HeatNT2WConv represents HTWater2Film.

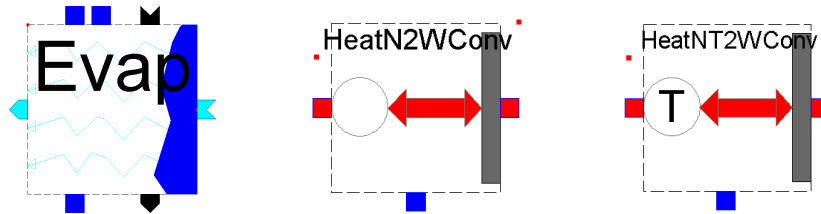


Figure 6.11: The three sub-models from the water segment that has been modified when implementing new diffusion equations.

6.6 Verification of the condenser

The same test bench used during the validation of the humidification tower was used to model the condenser. The only difference was that the humidifier model was exchanged with the new condenser model. The availability of measurement values suggested that the condenser model should be verified as a humidification tower. This would also verify the possibility to use the model as both a humidifier and condenser.

The condenser model showed a huge speed increase in simulation time compared to the old humidifier model. A 20 second simulation of the humidifier took about eight hours while it took five minutes for the condenser. The big time difference of course makes it easier to evaluate the model. One contributing factor to the increased speed is that there were cyclic dependencies between some equations, see equation 6.6, which could be very time demanding.

$$\begin{aligned}
 A &= f(B) \\
 B &= f(C) \\
 C &= f(A)
 \end{aligned}
 \tag{6.6}$$

Another reason for the speed increase is that fewer calculations are needed in the new model due to the less number of gas volumes. Also, the simulation results from the old humidifier model showed that the pressure derivatives for the segments were oscillating, see Figure C.3 and C.4 in Appendix C. This may cause stiff behaviour of the model, resulting in high simulation times. The new model's pressure derivative calculation prevents such oscillations.

The verification started with the most basic features of the model. This includes checking the direction of the gas and water flow. The gas has to flow upwards while the water of course is supposed to flow downwards in all ten water volumes. The result is presented in Figure D.1 and D.2 in Appendix D. It shows that both gas and water flows in the right directions, with approximately the desired velocities.

The direction of the evaporation mass flow should also be verified. Plots from the water volumes should show a negative value, which means that the mass leaves the water volume and enters the gas volume. This was positively verified. The plots are seen in Appendix D in Figure D.3.

After this rudimentary verification the absolute values of pressure, temperature, and mass flow were studied. They were acceptable but could be better. The pressure and gas outlet temperature was too low, while the outlet water temperature was higher than expected. Evaporation was also too low at first. The conclusion of this is that the energy exchange is not enough. If more energy, in this case heat, could be transferred from the water side to the gas side it would probably give the desired temperatures. A raise of the mass transfer coefficient h_d should increase both evaporation and heat transfer to gas, and thereby increase the pressure. Finally the mass flow value of the outlet water was almost as expected, see Figure D.4 in Appendix D, which means that enough water was evaporated. Still, the temperature was a bit too low. The problem that the energy exchange, and thereby the gas outlet temperature, does not raise enough, may be eliminated if the mass transfer coefficient varied between the water segments in the bottom and top. A higher mass transfer coefficient in the top would increase the gas temperature in this area, while a lower coefficient in the bottom would decrease the water temperature in the bottom.

A simulation was done to check if the assumption that the condenser also works as a humidifier. This showed to be successful with a condensation process instead of evaporation between the gas and water volumes.

Dynamic validation of the condenser model

A dynamic validation was done on the model. The dynamic values were taken from the humidification tower at the pilot plant at LTH, and were recorded in February 2002. The dynamic values contained a load raise from 40% to 50%, from 50% to 60%, and an emergency stop. The condenser validation was done on the 40% to 50% load increase. The gas pressure and gas temperature, the water pressure and water temperature, and the mass flow of the water are inputs to the model. A test bench that could handle dynamic values was created.

The validation gives the same results as when verifying the model. The mass flow rate is the desired, while the gas outlet temperature is too low and the water outlet temperature is too high, see Figure E.1 and E.2 in Appendix E.

The conclusion is the same as for the static verification. The energy transfer needs to increase.

6.7 Analysis/Evaluation

The model consists of ten segments. To make an exact model the number of segments would be very large. When modelling it is desired to be able to increase and decrease the number of segments, and even the gas volumes, with not much work, in order to have the freedom to decide the accuracy. This is a drawback with the model. It is highly possible to add segments but modifications of the model Friction, FlowGas, SumHeat, and gas volumes would be necessary.

The condenser model showed to be much faster than the humidification tower when simulating, which is a big advantage.

To evaluate how well the designed model works as the real humidification tower at LTH simulated values are compared with the measurement values from the pilot plant. Table 6.1 below shows the desired outlet gas and water mass flows, and temperatures, compared to respective simulated values. The gas and water flows are almost exact, while the simulated outlet gas temperature is about five degrees too low, and the outlet water temperature is a few degrees too high, see Figure D.4, D.5, D.7 in Appendix D. This gives the conclusion that the heat transfer between gas and water is not enough.

	gas flow (kg/s)	gas temp (°C)	water flow (kg/s)	water temp (°C)
pilot plant measurements	2.586	117	5.635	88
simulated model	2.583	104	5.636	91

Table 6.1: Measurement values from the pilot plant at LTH compared with values after a simulation of the designed model.

The decrease of gas volumes from ten to only two may be the reason for problem with transferring enough energy from the water to the gas during the evaporation. A simplification of the model with for example four gas volumes would probably give a higher energy transfer, without affecting the simulation speed very much.

In the humidification tower the parameters α_g , α_w , a , and b have to be determined by guessing or from approximate values from tables. This uncertainty has been eliminated and instead only one parameter h_d needs to be set. It would have been desired to also eliminate h_d , which is possible with quite extensive calculations. A calculation of the mass transfer coefficient may have solved the verification problem with the heat transfer.

Because the modelled condenser also works as a humidifier it should be used as both components when modelling the complete cycle. This would simplify maintenance of the model.

7 Discussion and conclusion

The objectives of this thesis were to first study and validate the humidification tower, and then create a model of the flue gas condenser. The design of the condenser model would be made with the humidification tower model as a starting point, because of the similarities between the components.

The mass transition between water and gas is possible in both directions, which gives the conclusion that the condenser model should be used even as a humidifier model. The only difference between the two components is the mass transition, evaporation in the humidifier, and condensation in the condenser. By initiating the model with different inlet temperatures either of these two processes will occur.

The modelled condenser consists of only two gas volumes instead of ten as for the humidification tower model. The decrease of number of the gas volumes means a decrease of the number of calculations in the condenser model. Thus, fewer calculations mean an increase in simulation speed. Modelling with a few more gas volumes would probably not affect the speed very much, but problems with transferring heat would decrease.

The condenser model showed a huge speed increase in simulation time compared to the old humidifier model. Cyclic dependencies between some equations that does not exist in the condenser model, is a reason why the simulation is so much faster. Also, the simulation results from the old humidifier model showed that the pressure derivatives for the segments were oscillating. This may cause stiff behaviour of the model, resulting in high simulation times. The new model's pressure derivative calculation prevents such oscillations.

The implementation of the evaporation calculation with the mass transfer coefficient h_d was successful. With this the heat transfer was raised compared to the humidification tower model, though not enough. To further improve the model the effort should be made on the evaporation or condensation, i.e. when water changes phase between liquid and gas.

When validating and verifying the designed condenser model the simulated values of outlet mass flow and temperature of the gas and water was compared to measurement values from the pilot plant at LTH. It was successful, with the exception of the heat transfer between gas and water that was a bit too low.

8 Further work

After the thesis work during the six months there still remains work to be done on the condenser model.

The most critical part when modelling was found to be the evaporation or condensation, i.e. when water changes phase between liquid and gas. To further improve the model this is where the effort should be made.

The mass transfer coefficient h_d now is a parameter whose value are approximate. With pretty extensive calculations it is possible to determine the value of the coefficient. The results would hopefully then be better and more exact than the ones today.

With more time also the interface should be studied. For example, mostly the parameter t stands for temperature in degree Celsius and T for Kelvin degrees. In some sub-models though, T stands for degree Celsius. This could cause big differences in the final results if value is described with Kelvin instead of Celsius.

Another problem with the models is the explanation of the function in words that is done within the interface. Many of the explanations of the ENERGY models need to be updated.

Further work also includes an implementation of the modelled condenser in the total EvGT-cycle.

Naturally all the models have to be verified to fit experimental data. This is a demanding task but will be necessary to make the final computer library a useful tool for design and operation of the EvGT process.

Nomenclature

A	Area	m^2
c	Velocity	m/s
c_p	Specific heat capacity	$kJ/(kg \cdot K)$
D_{ab}	Diffusion coefficient	m^2/s
h_d	Mass transfer coefficient	m/s
h	Specific enthalpy	kJ/kg
H	Enthalpy	kJ
\dot{m}	Mass flow rate	kg/s
M, m	Mass	kg
P, p	Pressure	Pa, bar
Q	Heat	kJ
R	Gas constant	$kJ/(kg \cdot K)$
RH	Relative humidity	-
t	Thickness	m
T	Temperature	$^{\circ}C, K$
u	Specific energy	kJ/kg
U, Q, W	Energy	kJ
v	Specific volume	m^3/kg
V	Volume	m^3
<i>Greek symbols</i>		
α	Heat transfer coefficient	$W/(m^2 \cdot K)$
ε	Emissivity	-
λ	Thermal conductivity	$W/(m \cdot K)$
ρ	Density	kg/m^3
ω	Humidity ratio	$kg \text{ component} / kg \text{ mixture}$
<i>Subscripts</i>		
g	Gas	
sat	Saturated	
sp	Structured package	
v	Vapor	
w	Water	

Appendix A

Gas

ENERGY gas table has ten gas components, N₂, CO₂, O₂, Ar, SO₂, CH₂, CO and H₂O, which are used in the gas volume. To calculate a new gas composition the following equation is used:

$$\frac{d\omega_x}{dt} = \frac{\sum_{i=1}^n (\dot{m}_i \cdot \omega_{x,i}) - \frac{dM}{dt} \cdot \omega_x}{M} \quad [\text{A.1}]$$

where ω_x , the humidity ratio, is the mass fraction of component x , M is the mass of the volume.

Partial pressure of the water vapour, which is the pressure the water would have if it existed alone in a volume, is calculated as follow:

$$p_{p,H2O} = \omega_{H2O} \cdot \frac{R_{H2O}}{R_{tot}} \cdot p_{tot} \quad [\text{A.2}]$$

where R is the gas constant for the gas mixture respective water.

The relative humidity is calculated according to:

$$RH = \frac{p_{p,H2O}}{p_{p,H2O,sat}} \quad [\text{A.3}]$$

Evaporation

$$\dot{m}_{evap} = \frac{ce \cdot 2 \cdot A \cdot M_{H2O}}{R \cdot (T_g + T_f)} \cdot (p_{H2O,f} - p_{H2O,g}) \quad [\text{A.4}]$$

where

$$ce = a \cdot |\dot{m}_w|^{(1-b)} \cdot |\dot{m}_g|^b \quad [\text{A.5}]$$

where a and b are constants.

Flow

$$\frac{dc_w}{dt} \cdot M_w = Fg_w - Fdp_w - Fm - Ff_w \quad [\text{A.6}]$$

$$\frac{dc_g}{dt} \cdot M_g = Fdp_g - Fg_g - Fm \quad [A.7]$$

The gravitational work is:

$$Fg_w = M_w \cdot g \quad [A.8] \quad \text{and} \quad Fg_g = M_g \cdot g \quad [A.9]$$

where $g=9.81$ is the acceleration of the gravity, which is constant, and M is the mass of water and gas respectively.

The pressure force calculations are:

$$Fdp_w = dp \cdot Ah_w \quad [A.10] \quad \text{and} \quad Fdp_g = dp \cdot Ah_g \quad [A.11]$$

where Ah is the cross-sectional area normal to flow direction of the segment. dp is the difference between the two pressures calculated in interconnected upper and lower volumes.

The friction calculation between water and gas is:

$$Fm = \frac{(c_g + c_w)c_g + c_w}{2} \cdot \rho_g \cdot \frac{L \cdot f_g}{dh_g} \cdot Ah_g \quad [A.12]$$

where c is the fluid velocity of the water and gas, ρ is the density, L is the length of the segment, f is the friction factor, and dh is the hydraulic diameter.

The friction calculation between water and walls is:

$$Ff_w = \frac{(c_w)c_w}{2} \cdot \rho_w \cdot \frac{L \cdot f_w}{dh_w} \cdot Ah_w \quad [A.13]$$

Finally the mass flow calculations can be made:

$$\dot{m}_w = Ah_w \cdot c_w \cdot \rho_w \quad [A.14]$$

$$\dot{m}_g = Ah_g \cdot c_g \cdot \rho_g \quad [A.15]$$

Appendix B

Appendix B contains some of the static validation results of the humidification tower. The x-axis shows the time in seconds, and the y-axis shows the variables like pressure, mass flow, and temperature.

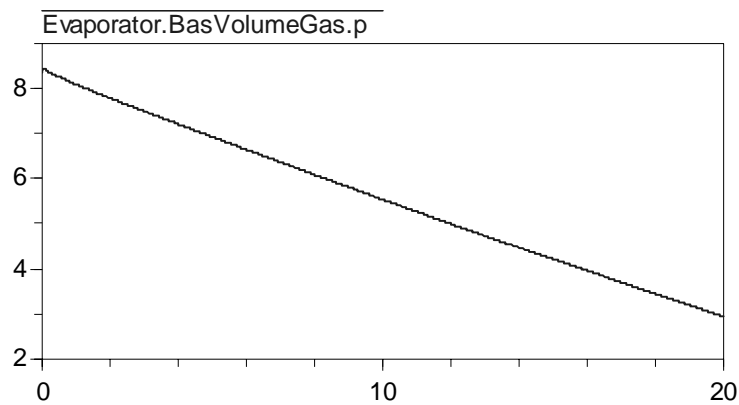


Figure B.1

The plot shows that the gas pressure is sinking from the desired value 8.356 bar.

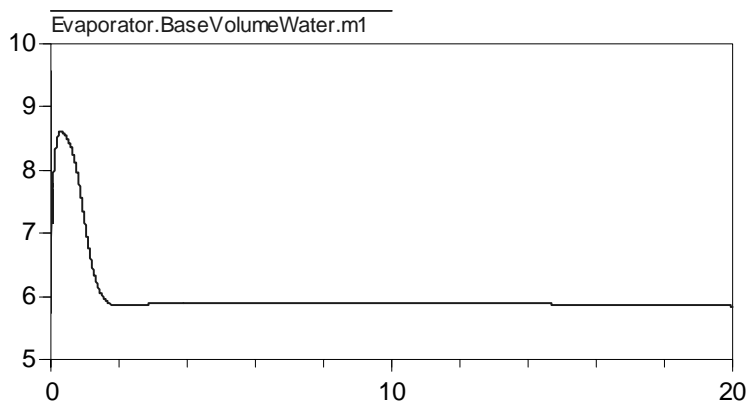


Figure B.2

The water mass flow outlet from the humidification tower should be 5.635 kg/s. Here the value is too high, 5.846 kg/s, which means that not enough water has been evaporated.

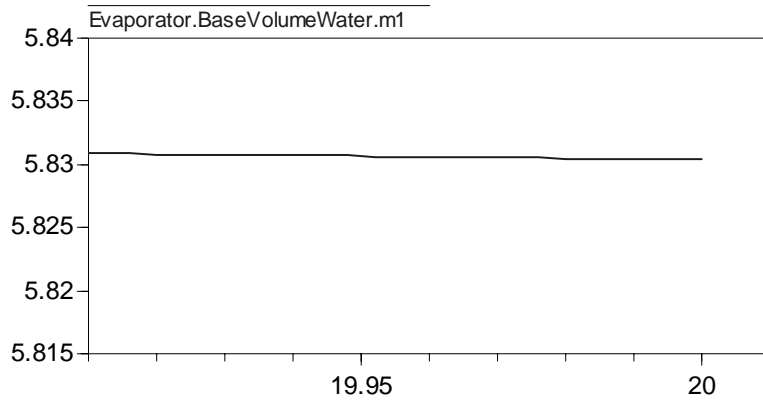


Figure B.3

The water mass flow is sinking when the heat transfer coefficient is changed from 0.13 to 0.2 and the surface roughness is changed from 1e-3 m to 3e-3 m. The best value of the mass flow was 5.831 kg/s, which is about 0.2 kg/s too high.

Appendix C

Appendix C shows some results from the humidification tower, which serves as the basis of the created sub-model FlowFriction. The x-axis shows the time in seconds, and the y-axis shows the variables like pressure, mass flow, and temperature.

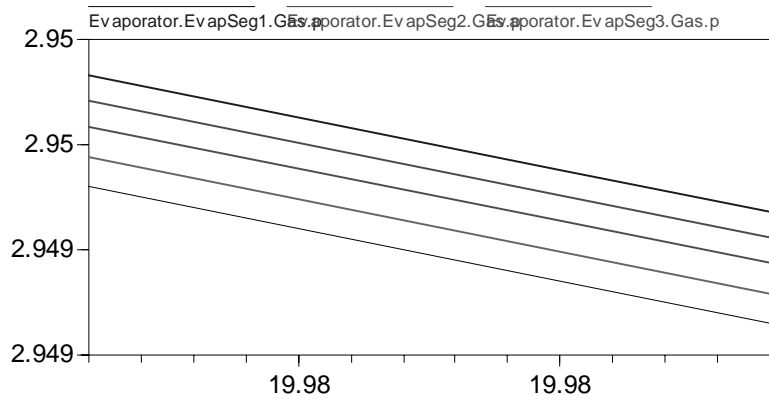


Figure C.1

Pressure of segment 1-5.

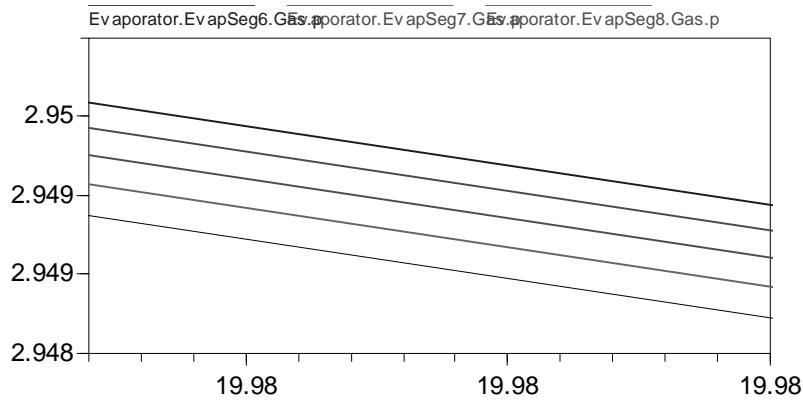


Figure C.2

Pressure of segment 6-10.

The two plots of the pressure above show that there are even distances between every segment.

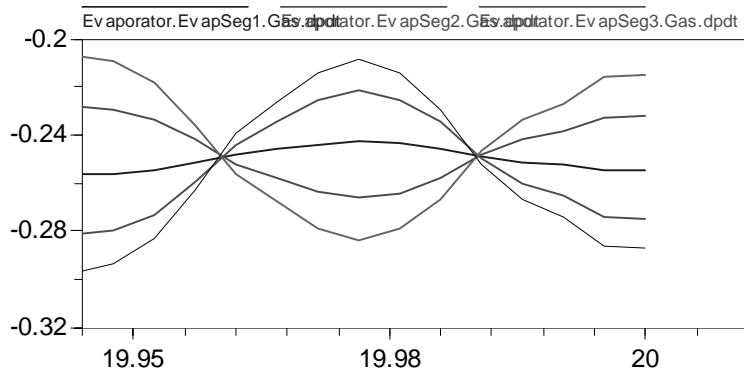


Figure C.3

Pressure derivative of segment 1-5.

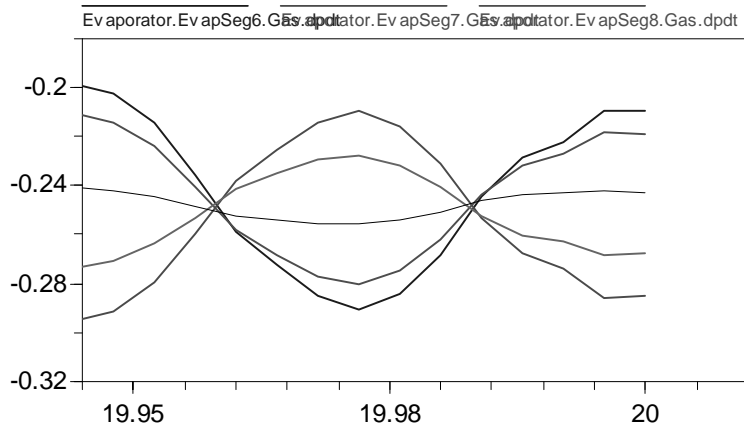


Figure C.4

Pressure derivative of segment 6-10.

The two plots of the pressure derivatives above show a fluctuation that is not desired.

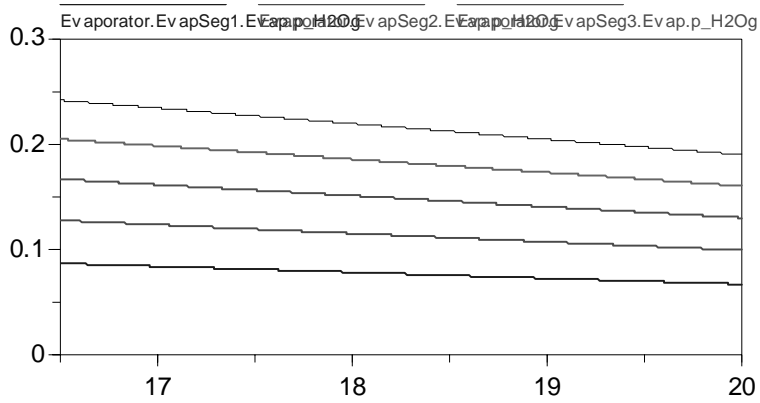


Figure C.5

Steam pressure of segment 1-5.

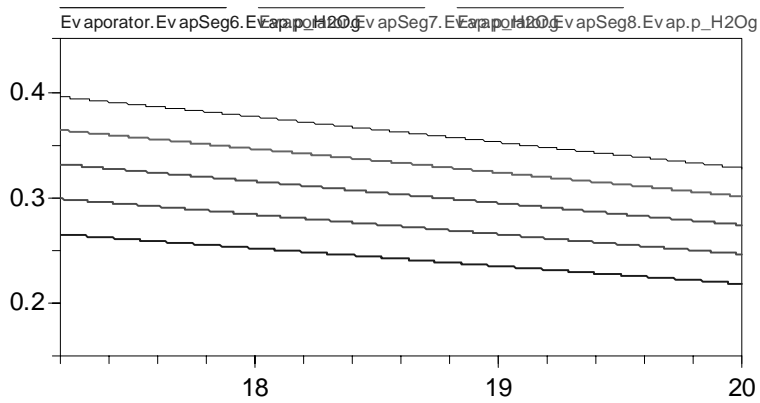


Figure C.6

Steam pressure of segment 6-10.

The two plots of the pressure above show that there are even distances between every segment.

Appendix D

Appendix D contains some simulation results from the verification of the condenser model. A positive value of a mass flow means that the medium is flowing into the volume and a negative means that it leaves the volume. The x-axis shows the time in seconds, and the y-axis shows the variables like pressure, mass flow, and temperature.

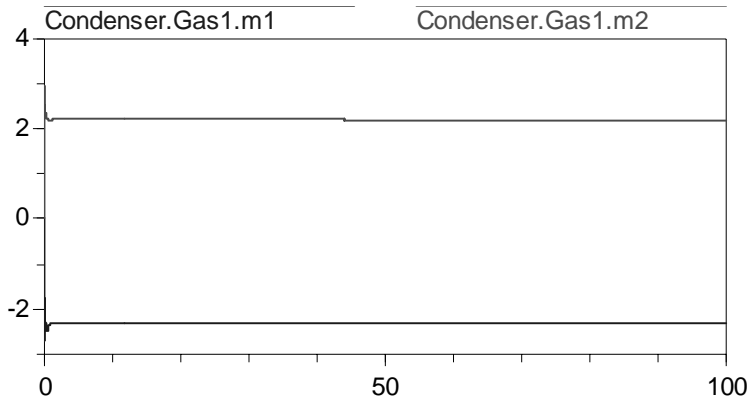


Figure D.1

The plot shows that the gas flows in right direction. Gas1.m1 is the inlet in the bottom of the gas volume while Gas1.m2 is the inlet on the top of the volume.

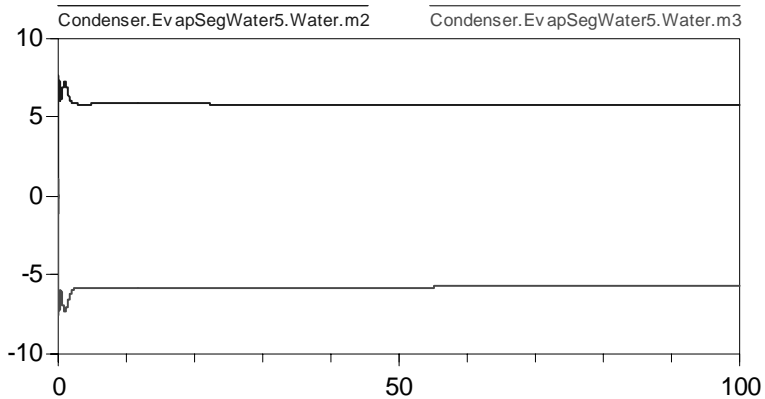


Figure D.2

The plot shows that the water flows in right direction. Water.m3 is the inlet in the bottom of the gas volume while Water.m2 is the inlet on the top of the volume.

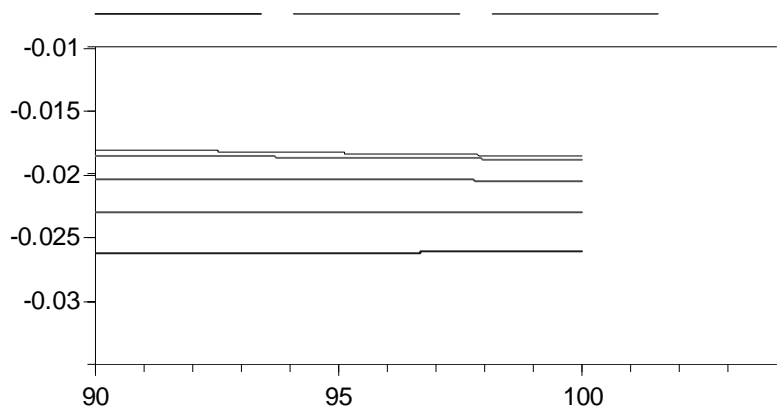


Figure D.3

The plot shows that the evaporation mass flow goes in right direction. The five lines represent the mass flow from five of the water segments. As seen the mass flow is negative, i.e. the mass is flowing out from the water volume which is desired in an evaporative process.

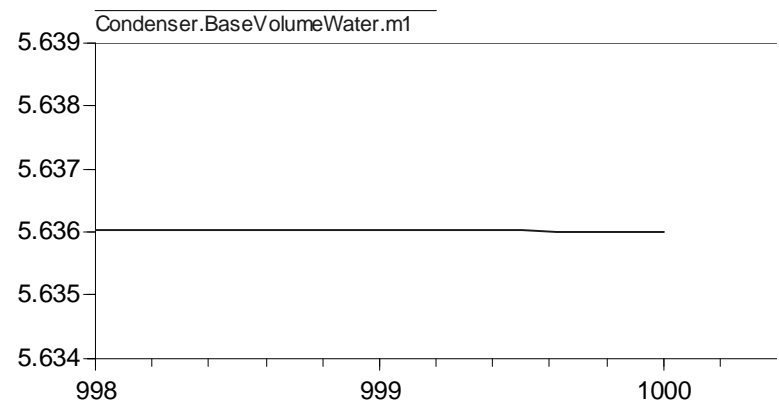


Figure D.4

The water mass flow outlet from the condenser should be 5.635 kg/s. An almost exact value is achieved after adjusting the diffusion coefficient.

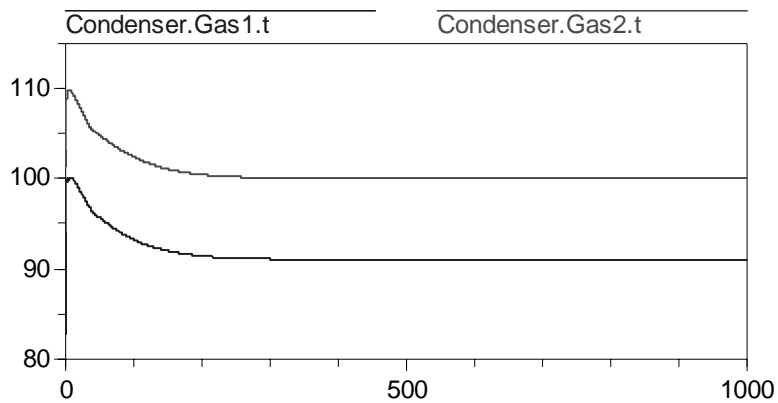


Figure D.5

The plot shows the gas temperature for the lower, Gas1, and the upper, Gas2, gas volumes. Gas2.t should be about 117 °C and is a bit too low.

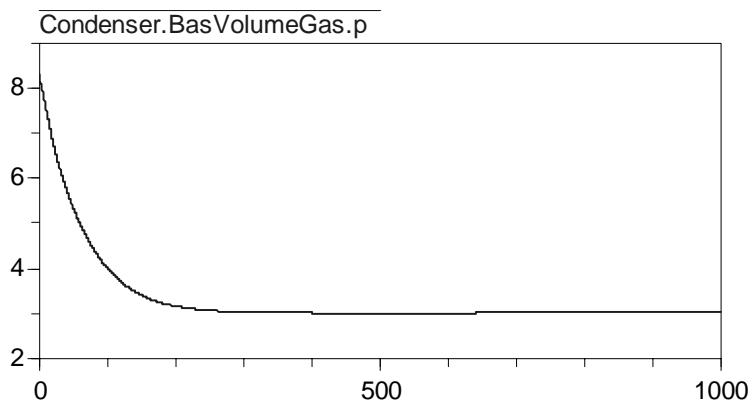


Figure D.6

The pressure is sinking from the desired value of 8 bar.

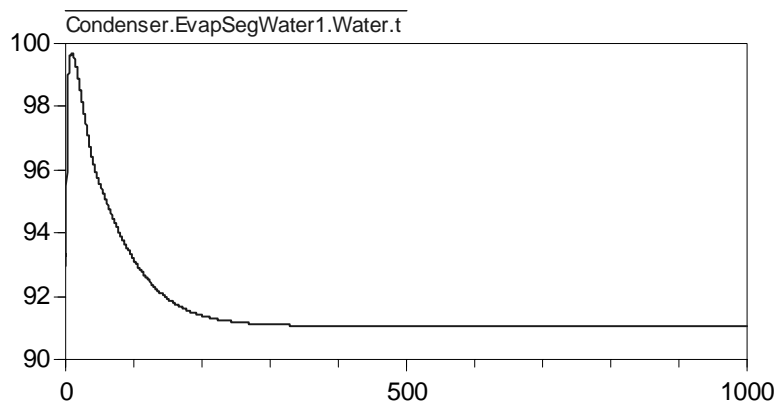


Figure D.7

The desired water temperature is 88.25 °C, which means that it is too high.

Appendix E

Appendix E shows the dynamic validation of the condenser model. The dynamic includes a load trip from 40% to 50%. The x-axis shows the time in seconds, and the y-axis shows the temperature.

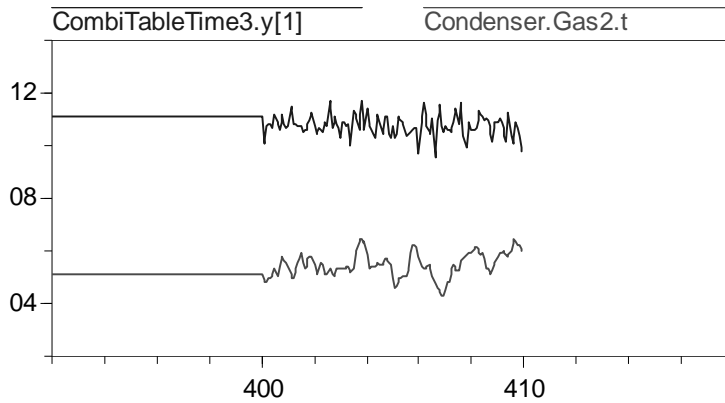


Figure E.1

Gas2.t shows a lower temperature than the value from the pilot plant.

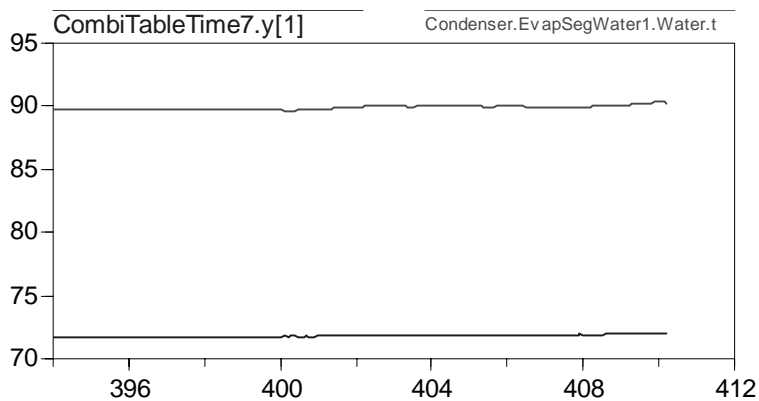


Figure E.2

Water.t shows that the temperature of the outlet is higher than the value from the pilot plant.

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