Simulation Model of Flue Gas Condensation Unit

And

Complete Process Plant Simulation

“Case Study of ENA Energi”

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Abstract

In line with the Swedish environmental policies, an important aim for ENA Energi AB is to reduce emissions and optimise the energy production from the main biomass-fired CHP plant. This is perceived to be achievable either by increasing the efficiency in the current facilities or introducing new energy supply systems with better material turn over characteristics.

This master thesis has been initiated to develop a complete process plant model for the main biomass-fired CHP plant using the commercial software IPSEpro. Earlier studies have produced the boiler and turbine models and the task of this study is to develop a model for the flue gas condenser and couple the models into one complete model of the plant, with the aim that this complete model can be used to make off design calculations and for optimisation purposes.

The flue gas condensation unit was modeled in IPSEpro and coupled to the existing boiler and turbine model. The models were simulated and validated with values taken from ENA Energi database. The simulated data shows good agreement with the real plant data and thus meet the objective of the study.

Keywords: CHP plant, Flue gas Condensation, Dew point, Saturation pressure, and partial pressure.

Nyckelord: Kraftvärmeverk, Rökgaskylare, Daggpunkt, Mättuadstryck, Patialtryck.
Preface

This master thesis has been carried out at the Department of Public Technology at Malardalen University in Vasteras. The study was carried out in collaboration with ENA Energi AB in Enkoping in the winter and spring of 2007.

My sincere appreciation goes to all the staff and personnel of ENA Energi AB, for their support during the last six months of this work and most importantly I say a big thank you for all the ‘fika’. Special thanks goes to Eddie Johansson for his support and providing me with the opportunity to conduct this research at ENA. I am also most grateful to my supervisor at ENA, Urban Eklund for his support and wealth of knowledge.

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I am most grateful to my supervisor at the Department of Public Technology Fredrik Starfelt for his precious guidance throughout this work, patience, support with my simulation tool IPSEpro, for providing me all information I needed and for answering my numerous questions.

Finally, to my wife and family I say thank you for your unconditional support throughout my education in Sweden.

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<tbody>
<tr>
<td>$h_{FG}$</td>
<td>Specific enthalpy of flue gas</td>
<td>J/kg</td>
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<tr>
<td>Q</td>
<td>Heat Transferred</td>
<td>kW</td>
</tr>
<tr>
<td>$m_{DHW}$</td>
<td>Mass Flow Rate of District Water</td>
<td>Kg/s</td>
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<td>$C_p$</td>
<td>Specific Heat of Water</td>
<td>J/KgK</td>
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<td>t1</td>
<td>District Water Temperature at inlet of Condenser</td>
<td>°C</td>
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<tr>
<td>t2</td>
<td>District Water Temperature at outlet of Condenser</td>
<td>°C</td>
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<tr>
<td>t</td>
<td>Mean Temperature of Distract water over Condenser</td>
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<td>$m_b$</td>
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<td>g</td>
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<td>Molecular Weight of Flue Gas Mixture</td>
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<td>Tdew</td>
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<td>$p_a$</td>
<td>moisture Vapor pressure</td>
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<td>Flue Gas Temperature out of the Condenser</td>
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<td>$V_{uncon}$</td>
<td>Uncondensed Moisture at the exit of Condenser</td>
<td>mol/Kg fuel</td>
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<tr>
<td>$V_{in}$</td>
<td>Moisture Content in Flue Gas</td>
<td>mol/Kg fuel</td>
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<tr>
<td>$L$</td>
<td>Latent Heat of Vaporization</td>
<td>KJ/kg</td>
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<td>flue gas mean temperature</td>
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1 Introduction

1.1 Background

Combined heat and power (CHP) is the simultaneous generation of heat and electricity in a single process. In conventional CHP power plants the heat from steam condensing after the steam turbine is used for heating, for example in district heating or cooling systems using heat pumps, instead of cooling it with a cooling tower or water from a lake. In the case of industrial CHP plants the steam can also be extracted in higher pressures from the turbine and used as process heat. The fuel consumption can be decreased with approximately 25-35% with CHP plants compared to the power and heat generation in separate processes (Cogen Europe et al. 2001). Thus the carbon dioxide (CO2) emissions per produced heat and power are reduced and the total efficiency of the generation increases.

ENA Energi AB is the main supplier of district heating and electricity in the city of Enkoping. It operates a CHP plant, equipped with a biomass-fired boiler, which supplies the Enkoping city areas with hot water for space heating of apartments, offices and industrial facilities and for the production of hot tap water. The district hot water circulates in a large, insulated, buried network of pipes. In each building, a heat exchanger is used to transfer the district heat to the buildings local net for further distribution of heat and hot tap water.

Beginning about two and a half decades ago, ENA Energi AB (formerly AB Enkoping Varmeverk) has continuously striven to decrease the environmental impact of services supplied. Biofuels i.e. wood pellets have replaced fossil fuelled boilers. Also to meet the increasing energy demand of the Enkoping community, in early 1990 a biomass-fired CHP plant was constructed in Enkoping with joint ownership between MalarEnergi AB of Vasteras and ENA Energi.
In line with the Swedish environmental policies, an important aim for ENA Energi AB is to reduce emissions and optimize the energy production from the main biomass-fired boiler. This is perceived to be achievable either by increasing the efficiency in the current facilities or introducing new energy supply systems with better material turn over characteristics.

As part of the ongoing efforts to develop an environmentally sustainable energy supply system, series of studies are being carried out at ENA Energi. This master thesis has been initiated to develop a complete process model for the main biomass-fired CHP plant using the commercial software IPSEpro. Earlier studies have produced the boiler and turbine models and the task of this study is to develop a model for the flue gas condenser and couple the models into one complete model of the plant.

Flue gas condensing is a method of simultaneously recovering energy and cleaning of flue gases. Hence with the use of a flue gas condenser, two main objectives are achieved at the same time, energy efficiency and reduced emission. The flue gas condenser will be modeled in IPSEpro and coupled to the existing boiler and turbine model to make a complete model of the plant with the aim that this complete model can be used to make off design calculations and for optimization purpose.
2 Company Description

2.1 General Information

ENA Energi AB operates a biomass fired CHP plant that produces 55MW heat and 25MW electricity. It is the main supplier of district heating and electricity in the city of Enkoping, (Enköping is a Swedish town with about twenty thousand (20,000) inhabitants).

![Diagram of District Heating System](www.enae.se)

The Power plant supplies the Enkoping city areas with hot water for space heating of apartments, offices and industrial facilities and for the production of hot tap water. In each building, a heat exchanger is used to transfer the district heat to the buildings local net for further distribution of heat and hot tap water, as depicted in figure 1 above.

The CHP plant also produces the major part of the electricity demand in the town. The municipality owns the company, so the profit goes to the people in the form of reduced district heating pricing. The CHP plant depends on fuel mix from forest industry waste.
material and short rotation crops called Salix. The forest industry waste material consists mainly of tops and branches from trees, sawdust and bark from the wood processing industry.

2.2 Environmental Consideration
Generating heat and electricity from fossil fuels is considered both in scientific and industrial circles to contribute to the increasing carbon dioxide content (CO$_2$) in the atmosphere, which is directly linked to global atmospheric greenhouse warming. A wide range of technologies are being investigated that increase the efficiency of electrical and heat production, decrease the energy needed to power electrical components, limit carbon dioxide and other greenhouse gas emissions etc. Consequently, the Swedish government has imposed CO$_2$ tax and energy tax on fossil fuel usage on power utility companies, which has driven a restructuring of the power companies from using fossil fuels to biomass from the forest industry, since there is a general consensus that combusting biomass contributes a net of zero CO$_2$ to the atmosphere.

ENA Energi aside turning to biomass for its power generation, it has also developed a biocyclical process where the bottom ash is mixed with dewatered digested sludge from the water purification plant which is spread as fertilizer on the Salix plantation, while the fly ash is used as terracing material to cover waste dump in a specified site. This serves to achieve two goals, increased production from the Salix plantation and environmentally sound disposal of waste material from the power plant.

To increase plant efficiency, the plant is also equipped with a flue gas condenser, which utilizes the heat content in the flue gas leaving the boiler for preheating the district heating supply before the main condenser and cleaning of the flue gases.
3 Methodology

The flue gas condenser model was developed in IPSEpro by creating the flue gas condenser (FGC) module in the model development kit (MDK). The flue gas was treated as an ideal gas with no heat losses to the surroundings. The flue gas composition was adapted from the boiler model, which contains about 26 % moisture content by volume, and was used as the basis of all calculation. The model was verified and validated with values taken from ENA Energi database, with conclusions drawn from the validation.

3.1 Objective

Previous studies have developed the models for both the boiler and turbine. To make a complete model of the plant it is required that a model of the flue gas condenser is developed. The complete model is seen as a tool that can be used in predicting the accuracy of the heat load and electrical power output.

In order to develop the model for the flue gas condenser, the commercial software IPSEpro is employed. A literature search was conducted on the application of flue gas condensers for predicting their performance when used in a biomass or coal cofired boiler.

This study focuses mainly on IPSEpro modeling of the flue gas condenser and connecting it to the turbine and boiler models to make a complete model for the ENA Energi main biomass CHP plant. The main objectives of this study are listed in the following points:

- Connect the existing models and develop the flue gas condenser model in IPSEpro to obtain a complete model of the ENAE plant
- Analyze and tune the steam turbine model to work with the boiler model
- Construct the model to work from min to max load
- Verify that the model respond as the actual plant
- Present a base for future work in making off design calculations.

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3.2 Limitations

There are two areas of limitation to this study:

1. No transient calculations are performed. This is not compatible with the software IPSEpro.

2. The study is limited to developing the model in design consideration alone. Off design calculations and optimization will be the basis for future study.

3.3 Energy in Flue Gases

The exhaust gases of conventional boilers exit the stack at temperatures between 130–200°C, carrying a considerable amount of energy along with it. An important consideration for the use of biomass fuel in power plants is the treatment of biomass flue gases to recover some of the energy in the flue gas. When the flue gas is cooled to a temperature below the dew point, the water vapor condenses and some of the energy that would have been lost in the stack can be recovered.

3.3.1 Heat recovery methods

Heat loss in flue gases can be substantially reduced by equipment that diverts the thermal energy in flue gases to other parts of the boiler plant. For example, heat exchangers called economizers transfer heat from flue gas to boiler feedwater, and combustion-air preheaters use the energy in hot flue gases to heat combustion air.

3.3.2 Flue gas condenser

A particularly energy-efficient heat recovery option is the direct-contact flue gas condensing unit, which sprays water through the flue gas stream and passes the heated spray water through a heat exchanger to transfer the heat to the district heating water or other plant processes. Flue gas condensers recover the latent heat of vaporization and much of the sensible heat from water vapor in the flue gas. An incidental advantage of direct-contact flue gas condensing is that it removes particles and acid gases (such as SO₂) from the exhaust.
4 Simulation Tool and Process Models

To model the Flue Gas Condensing unit as well as to calculate the heat and energy demand for the biomass fired CHP plant at ENA Energi, the industrial software IPSEpro was used. IPSEpro is an equation-oriented simulation tool designed for power engineering use. The software tool consists of two parts (Perz, 1990) the process simulation environment (PSE) in which whole process configuration can be modeled and the model development kit (MDK) in which single user defined units can be created.

Compared to other simulation tools (ASPENplus, CHEMCAD,...) which focus on the detailed calculation of single process units, or other softwares like Prosim which posses similar structure to IPSEpro but with longer processing time, the flexible structure of IPSEpro in terms of extensibility and its origin confirm the choice for implementing models of the present topic (D. Häggstål & E. Dahlquist, 2003).

4.1 The Process-Modeling Environment IPSEpro

IPSEpro is a flexible and comprehensive software environment for modeling and analyzing processes in energy engineering, chemical engineering and many other related areas. IPSEpro allows the user to create process models graphically by appropriately connecting component models from a library. For setting up the process model a graphic process scheme editor is available. IPSEpro is a MS-Windows package.

At the core of the software package is the capability to build process models from components, typically representing individual pieces of equipment, like heat exchangers, pumps, etc. IPSEpro is a software framework. It strictly distinguishes between the actual program and the application specific component models. Built-in component models do not limit the user: The component models are organized in model libraries, which contain all component specific information, from graphical appearance to the equations that describe the behavior of the components. The user can modify existing model libraries and create new ones. This makes it possible to adjust IPSEpro for new fields of application without modifying the program itself. IPSEpro consists of several major modules. Fig. 2 shows the
basic architecture of the software package. The main features of the modules are described below.

4.1.1 PSE: Process Simulation Environment
PSE is used to create and solve process models based on components from a library. PSE provides a graphic flow sheet editor for setting up process models. The user selects the required components from the library menu and arranges them appropriately. All process data is entered directly in the flow sheet. PSE generates output protocols automatically and displays the results in the flow sheet, at the end of a simulation run.

4.1.2 MDK: Model Development Kit
MDK, IPSEpro’s model development kit, provides the capabilities that are required to define new models and to translate them into a form that can be used by PSE. MDK consists out of two functional units:
• Model editor
• Model compiler
The model editor allows the user to design icons that represent the models and to describe the model behavior mathematically in the form of model equations. And the MDK model compiler translates the model descriptions into a binary format that guarantees high performance when a process model is solved.

4.2 The Flue Gas Condenser Model
The steady state simulation program IPSEpro was used as noo detailed time dependent analysis is considered. The mass and energy balance equations are written from the law of conservation of mass and energy, while the flue gas and water physical properties are
provided with the IPSEpro Advanced Power Plant Library (APP) in the dynamic link library (DLL). However IPSEpro also provides the flexibility for user defined characteristic function in DLL.

4.2.1 Flue Gas Composition
The flue gas enthalpy is determined by the composition of the gas, wherein the composition of the gas is determined by the fuel (in this case biomass) composition and the amount of excess air. Although the composition of the fuel vary with type of fuel source, mix and moisture content, for the purpose of this study, the fuel composition is set at a fixed composition derived from the boiler model and is presented below:

With this composition the flue gas composition is calculated and derived from the boiler model.

4.2.2 Flue Gas Enthalpy
The enthalpy of the flue gas is evaluated in DLL at the operating temperature and pressure and is influenced by the enthalpies of the constituents of the gas and composition.

\[
 h_{FG} = FG.\text{Composition.fhpt}(p, T) 
\]

Where \( p \) is the total pressure (bar) of the gas and \( T \) is the temperature (°C) of the gas.

The difference in the enthalpies of the gas at the inlet and at the outlet with the heat of condensation of the water vapor in the flue gas will be the heat used to raise the district water return temperature before the main condensers.

4.2.3 Heat Recovered
The total heat that can be recovered from the flue gases is dependent on the size of the boiler, moisture content of the fuel and excess air used in the combustion. The size of the boiler determines the amount fuel burnt and thus determines the mass flow of the flue gases; whereas the moisture content of the fuel determines and excess air determines the gas

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composition, which indirectly determines the dew point and amount of energy that can be recovered from the flue gases.

### 4.2.4 District Heating Water

The heat transferred from the flue gas to the district heating water can be estimated from the district heating water (DHW) mass flow, specific heat capacity of water and the change in temperature of the DHW over the flue gas condenser as given below:

\[
Q = m_{\text{DHW}} \times C_{pw} \times (t_2 - t_1) \]

Where \( t_1 \) and \( t_2 \) are the DHW inlet and outlet temperature respectively, \( C_{pw} \) is the specific heat capacity of water. An estimate for the specific heat capacity of water is provided by the equation below.

\[
C_{pw} = 2820 + 11.82t - 0.03502t^2 + 0.00003599t^3
\]

Where \( t \) as used in equation 3 above is the mean temperature between the inlet and outlet temperature of the DHW with its unit in Kelvin.

### 4.2.5 Flue gas

The heat released by cooling down the flue gases is what the district heating water absorbs. This heat released can be estimated by dividing it into four stages.

- Cooling of flue gas from the exhaust temperature from the boiler to the dew point.
- Heat that is released from condensation of the water vapor in the flue gas from the dew point to the exit temperature of the flue gas.
- Heat released by the dry flue gases and uncondensed water vapor from the dew point to the flue gas exit temperature.
- Heat released from cooling of the condensed water vapor.

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4.2.6 Sensible Heat

The exhaust gases leave the boiler at temperatures between 130-200°C and the energy they carry with them constitute the major losses in a boiler. The temperature at which condensation starts to occur is called the dew point. We can estimate how much energy (i.e. sensible heat) is released from cooling the flue gases from the boiler exit temperature to the due point. This is can be estimated from the relationship below:

\[ P_1 = m_b \cdot g \cdot MW_{FG} \cdot (h_{FGin} - h_{FGdew}) \] \hspace{1cm} 4

Where \( P_1 \) is the heat released during cooling, \( m_b \) is the fuel flow in kg/s (dependent on the boiler load); \( g \) is the molar flow of the flue gases per fuel; \( MW_{FG} \) is the molecular weight of the flue gases, and \( h_{FGdew} \) and \( h_{FGin} \) are the enthalpies of the flue gases at the dew point temperature and inlet temperature respectively.

This requires estimating the dew point temperature and gas flows.

4.2.7 Dew Point

The water vapor content of the gas is often referred to as the dew point. This is the temperature to which the flue gas will be cooled before vapor in it starts to condense. This is the temperature at which the actual vapor content is equal to the saturation vapor pressure. The saturation vapor pressure is usually retrieved from a table, however for the purpose of this study, the dew point is estimated from the empirical formula proposed by Tetens O., (1930), that is

\[ T_{dew} = \ln(p_a \cdot 10^4 / 610.78) \cdot 238.3/(17.294 – \ln(p_a \cdot 10^4 / 610.78)) \] \hspace{1cm} 5

Where \( T_{dew} \) (°C) is the dew point temperature at the actual vapor pressure \( p_a \) (bar) or the partial pressure of the moisture content in the flue gas.

\( p_a \) is estimated as

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\[ p_a = p \left( \frac{y_{H_2O}}{MW_{H_2O}} \right) \left( \frac{m_{FG}}{m_f \cdot g} \right) \]  \hspace{1cm} (6)

Where \( p \) is the total pressure of the flue gas, \( y_{H_2O} \) and \( MW_{H_2O} \) are the mass fraction and molecular weight of water vapor respectively, \( g \) is the molar flow of flue gas and \( m_{fg} \) is the mass flow of flue gas.

### 4.2.8 Molar Flow
The molar flow \( (g) \) is the number of moles of the flue gases per kilogram of fuel. It is required to determine the amount of dry and wet flue gases. The molar flow is estimated from the gas composition and is influenced by the excess air used in the combustion.

The molar flow is given as
\[ g = \frac{m_{FG}}{m_f} \left( \sum (y_i \cdot MW_i) \right) \]  \hspace{1cm} (7)

Where \( m_{FG} \) is the mass flow of the flue gas, \( y_i \) and \( MW_i \) are the mass ratio and molecular weight of flue gas components respectively.

The sensible heat can be estimated from equation 4 above once the fuel flow, flue gas composition, total pressure of the flue gas and the flue gas boiler exit temperature is known.

### 4.2.9 Heat of Condensation
Flue gases often contain large quantities of moisture; with the result that there is plenty of energy available for recovery from it due to condensation. The moisture in the flue gas comes from three sources: fuel moisture, water vapor formed from the oxidation of fuel hydrogen, and water vapor carried into the boiler with the combustion air. Figure 3 shows the potential for heat recovery from the flue gases of a biomass-fired boiler.
The latent heat of condensation of the moisture in the flue gas is the most significant of all energy available in the gas. When the gas is cooled to the dew point temperature, it starts to condense. The condensation involves only a phase change at the dew point without a change in temperature. To model this in IPSEpro, an estimate of the condensed vapor is made, with the assumption that the flue gas is saturated at exit temperature, which gives the saturation pressure after the condenser.

The saturated pressure out of the condenser can be estimated by reversing the Tetens equation of 5 above.

\[ p_{\text{sat out}} = \frac{(610 \cdot \exp(T_{\text{out}} / (T_{\text{out}} + 238.3) \cdot 17.2694))}{10^4} \]  

Where \( p_{\text{sat out}} \) (bar) is the saturation temperature of the water vapor at the exit temperature and \( T_{\text{out}} \) is the exit temperature of the flue gas after the condenser.

Assuming an ideal gas for the water vapor the concentration. The relationship for the vapor pressure and concentration is given for ideal gases as

\[ p = \frac{nRT}{V} \]

Thus we can estimate the amount of uncondensed vapor at the exit temperature \( T_{\text{out}} \) and vapor pressure \( p_{\text{sat out}} \).
Where \( V_{\text{uncon}} \) (mol/Kgfuel) is the uncondensed vapor in the exit flue gas, \( g_{\text{dry}} \) is the dry flue gas without any moisture content and \( p \) is the total pressure of the flue gas.

The condensed moisture is estimated by subtracting the uncondensed vapor from the initial vapor in the flue gas at the inlet of the condenser. The heat of condensation can then be estimated as

\[
P_2 = m_b \times (V_{\text{in}} - V_{\text{uncon}}) \times l \times MW_{H_2O} \tag{11}
\]

Where \( V_{\text{in}} \) is the initial moisture content of the flue gas, \( l \) is the latent heat of condensation and \( P_2 \) is the heat recovered due to condensation. The latent heat of vaporization \( (l) \) was obtained by fitting curves to values from the table and diagram (Lars Wester, 2003) between 40-70°C. The curve shows a linear fit as presented below.

![Figure 4: Curve fit of latent heat of vaporization](image)

Thus the latent heat of vaporization can be estimated at temperatures between the dew point and the exit temperature of the flue gas.

That is

\[
l = -2.4312 \times T_m + 2503.4 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots

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4.2.10 Heat of Cooling

Some heat is also recovered from cooling the uncondensed flue gases and the condensed vapor from the dew point to the exit temperature, although both of this is small when compared to the heat recovered from condensation and sensible heat of the flue gas.

The heat recovered from cooling of the dry flue gas is estimated as follows

\[ P_3 = m_b \cdot (g_{dry} + V_{uncon} + \frac{(V_{in} - V_{uncon})}{2}) \cdot C_{pw} \cdot (T_{dew} - T_{out}) \] ..................13

Where \( g_{dry} \) is the molar flow of dry flue gas and is estimated as in equation 7 excluding the composition of the water vapor content. Where the expression in bracket can be taken as the mean flow of dry gases through the condenser.

The cooling of the condensed water is estimated as shown below, however this constitute a small portion of the total energy that can be recovered from the flue gas.

\[ P_4 = m_b \cdot \frac{(V_{in} - V_{uncon})}{2} \cdot C_{pw} \cdot (T_{dew} - T_{out}) \] ..................14

The total energy recovered from the flue gas is the sum of the estimated energies from equations 7,11,13 and 14.

\[ Q = P_1 + P_2 + P_3 + P_4 \] ..................15

4.2.11 Log Mean Temperature Difference

To estimate the heat recovered in IPSEpro it is required to predict the temperature \( T_{out} \) of the flue gas after the condenser. To achieve this the log mean temperature difference was employed and the exchanger is treated as a counter flow heat exchanger.

\[ Q = UA \cdot (\Delta T_{out} - \Delta T_{in}) / \ln(\Delta T_{out} / \Delta T_{in}) \] ..................16

Where \( \Delta T_{in} = T_{in} - t_2 \) and \( \Delta T_{out} = T_{out} - t_1 \)

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The operations points in the database of ENA Energi were used to estimate the heat transfer area (i.e. UA value) by fitting a curve to the heat transfer area as a function of the power recovered from the flue gas. Figure 5 below shows the curve fit for the heat transfer area as a function of power.

![Figure 5: Curve fit for Heat Transfer Area](image-url)

\[
y = -7E-07x^2 + 0.0341x + 64.638 \\
R^2 = 0.831
\]
5 Result/Validation

5.1 Flue gas condenser
The flue gas module was simulated at four loads for validation and it shows good agreement with some variation as can be seen below. The actual data are data taken randomly from operating points of interest.

![Flue gas condenser simulation output](image)

The results for the simulations are presented in the tables and graphs below and will be followed by analysis. The load as presented here corresponds to the relative load of the boiler, rather than the nominal load as the turbine load is designed to a maximum relative load of 90% corresponding to 100% nominal load.

Usman, Musibau
Table 1: Operation Data ENA database.

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>$m_{st}$ kg/s</th>
<th>$T_{gout}$ °C</th>
<th>$T_{in}$ °C</th>
<th>$m_{DH, st}$ kg/s</th>
<th>$m_{DH}$ kg/s</th>
<th>$T_{DHin, st}$ °C</th>
<th>$T_{DHout}$ °C</th>
<th>$T_{gout}$ °C</th>
<th>$T_{in}$ °C</th>
<th>$Q_{fgc}$ MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>17.08333315</td>
<td>50.98225</td>
<td>45.14063</td>
<td>268.5701</td>
<td>7.425157</td>
<td>53.49994</td>
<td>122.1959</td>
<td>9.665121</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>21.4554624</td>
<td>54.39443</td>
<td>47.39063</td>
<td>257.6525</td>
<td>-2.21422</td>
<td>57.1014</td>
<td>138.8664</td>
<td>10.8342</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>24.19873351</td>
<td>55.73259</td>
<td>49.67559</td>
<td>259.3215</td>
<td>0.174972</td>
<td>57.68374</td>
<td>145.3125</td>
<td>9.715774</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>25.51449606</td>
<td>54.9023</td>
<td>48.34027</td>
<td>286.2812</td>
<td>0.745204</td>
<td>56.78569</td>
<td>141.1875</td>
<td>10.49959</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Calculated Values from flue gas condenser simulation

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>$m_{st}$ kg/s</th>
<th>$T_{gout}$ °C</th>
<th>$T_{in}$ °C</th>
<th>$m_{DH, st}$ kg/s</th>
<th>$m_{DH}$ kg/s</th>
<th>$T_{DHin, st}$ °C</th>
<th>$T_{DHout}$ °C</th>
<th>$T_{gout}$ °C</th>
<th>$T_{in}$ °C</th>
<th>$Q_{fgc}$ MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>17.08333315</td>
<td>54.45</td>
<td>45.14063</td>
<td>268.5701</td>
<td>7.425157</td>
<td>53.64</td>
<td>122.1959</td>
<td>9.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>21.4554624</td>
<td>56.03</td>
<td>47.39063</td>
<td>257.6525</td>
<td>-2.21422</td>
<td>58.12</td>
<td>138.8664</td>
<td>10.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>24.19873351</td>
<td>58.22</td>
<td>49.67559</td>
<td>259.3215</td>
<td>0.174972</td>
<td>60.96</td>
<td>145.3125</td>
<td>12.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>25.51449606</td>
<td>57.96</td>
<td>48.34027</td>
<td>286.2812</td>
<td>0.745204</td>
<td>59.03</td>
<td>141.1875</td>
<td>12.79</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

♦ All values in green boxes are values from the ENA database.

Below the values from the simulation are compared with the values taken from the database of ENA and the relationships are shown graphically.

Table 3: Comparison of flue gas temperature out of the condenser

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>actual</th>
<th>Calc.</th>
<th>%error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{gout}$ °C</td>
<td>$T_{gout}$ °C</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>50.98225</td>
<td>54.45</td>
<td>6.368686</td>
</tr>
<tr>
<td>70</td>
<td>54.39443</td>
<td>56.03</td>
<td>2.919096</td>
</tr>
<tr>
<td>80</td>
<td>55.73259</td>
<td>58.22</td>
<td>4.272434</td>
</tr>
<tr>
<td>90</td>
<td>54.9023</td>
<td>57.96</td>
<td>5.275529</td>
</tr>
</tbody>
</table>

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Table 3: Comparison of District heating water temperature out of the condenser

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>actual Δt\textsubscript{DH}</th>
<th>calc. Δt\textsubscript{DH}</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>8,359316</td>
<td>8,50</td>
<td>-1,67549</td>
</tr>
<tr>
<td>70</td>
<td>9,71078</td>
<td>10,73</td>
<td>-10,4893</td>
</tr>
<tr>
<td>80</td>
<td>8,008154</td>
<td>11,28</td>
<td>-40,9116</td>
</tr>
<tr>
<td>90</td>
<td>8,445421</td>
<td>10,69</td>
<td>-26,5742</td>
</tr>
</tbody>
</table>

Figure 7: Heat Recovered from flue gas condenser
5.2 Complete Process Plant Simulation

The complete process plant was also simulated at four loads for validation with good agreement as with the values taken from the database. The actual data are data taken randomly from operating points of interest. The results are presented below:

Table 4: Operation Data ENA database.

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>mstitutional</th>
<th>Tgout°C</th>
<th>TDHin°C</th>
<th>mDH</th>
<th>Outdoor Temp°C</th>
<th>Tgin°C</th>
<th>Qfgc MW</th>
<th>Qmaincon MW</th>
<th>Qtotal MW</th>
<th>Tsupply °C</th>
<th>El effect MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>17.083</td>
<td>50.982</td>
<td>45.141</td>
<td>268.57</td>
<td>7.4252</td>
<td>53.5</td>
<td>9.6651</td>
<td>29.534</td>
<td>39.224</td>
<td>79.98</td>
<td>14.24</td>
</tr>
<tr>
<td>70</td>
<td>21.456</td>
<td>54.394</td>
<td>47.391</td>
<td>257.65</td>
<td>-2.214</td>
<td>57.101</td>
<td>10.834</td>
<td>38.223</td>
<td>49.114</td>
<td>92.97</td>
<td>18.03</td>
</tr>
<tr>
<td>80</td>
<td>24.199</td>
<td>55.733</td>
<td>49.676</td>
<td>259.32</td>
<td>0.175</td>
<td>57.684</td>
<td>9.7158</td>
<td>42.955</td>
<td>52.677</td>
<td>97.77</td>
<td>20.15</td>
</tr>
<tr>
<td>90</td>
<td>25.514</td>
<td>54.902</td>
<td>48.34</td>
<td>286.28</td>
<td>0.7452</td>
<td>56.786</td>
<td>141.19</td>
<td>45.066</td>
<td>55.544</td>
<td>94.49</td>
<td>21.69</td>
</tr>
</tbody>
</table>

♦ All values in green boxes are values from ENA database.

Table 5: Calculated Values from the complete process simulation

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>mstitutional</th>
<th>Tgout°C</th>
<th>TDHin°C</th>
<th>mDH</th>
<th>Outdoor Temp°C</th>
<th>Tgin°C</th>
<th>Qfgc MW</th>
<th>Qmaincon MW</th>
<th>Qtotal MW</th>
<th>Tsupply °C</th>
<th>El effect MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>16.69</td>
<td>53.46</td>
<td>45.14</td>
<td>268.57</td>
<td>7.4252</td>
<td>53.82</td>
<td>9.74</td>
<td>29.99</td>
<td>39.72</td>
<td>79.98</td>
<td>14.78</td>
</tr>
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<td>70</td>
<td>21.55</td>
<td>54.91</td>
<td>47.39</td>
<td>257.65</td>
<td>-2.214</td>
<td>57.16</td>
<td>10.55</td>
<td>38.82</td>
<td>49.37</td>
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</tr>
<tr>
<td>80</td>
<td>24.43</td>
<td>54.3</td>
<td>49.676</td>
<td>259.32</td>
<td>0.175</td>
<td>57.59</td>
<td>8.57</td>
<td>43.69</td>
<td>52.26</td>
<td>97.77</td>
<td>20.15</td>
</tr>
<tr>
<td>90</td>
<td>25.34</td>
<td>54.57</td>
<td>48.34</td>
<td>286.28</td>
<td>0.7452</td>
<td>57.5</td>
<td>10.95</td>
<td>44.39</td>
<td>55.34</td>
<td>94.49</td>
<td>21.69</td>
</tr>
</tbody>
</table>

The complete plant simulations are compared with the values taken from the database of ENA and the relationships are shown graphically.

Usman, Musibau
Table 6: Comparison of District heating water temperature out of the condenser

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>actual</th>
<th>calc.</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_{DHout} , ^\circ C$</td>
<td>$t_{DHout} , ^\circ C$</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>53.5</td>
<td>53.82</td>
<td>-0.59824</td>
</tr>
<tr>
<td>70</td>
<td>57.101</td>
<td>57.16</td>
<td>-0.10262</td>
</tr>
<tr>
<td>80</td>
<td>57.684</td>
<td>57.59</td>
<td>0.162507</td>
</tr>
<tr>
<td>90</td>
<td>56.786</td>
<td>57.5</td>
<td>-1.2579</td>
</tr>
</tbody>
</table>

Table 7: Comparison of flue gas temperature out of the condenser

<table>
<thead>
<tr>
<th>Boiler load%</th>
<th>actual</th>
<th>calc.</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{gin} , ^\circ C$</td>
<td>$T_{gin} , ^\circ C$</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>122.2</td>
<td>127.5</td>
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</tr>
<tr>
<td>70</td>
<td>138.87</td>
<td>138.5</td>
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<tr>
<td>80</td>
<td>145.31</td>
<td>145.3</td>
<td>0.00172</td>
</tr>
<tr>
<td>90</td>
<td>141.19</td>
<td>148.1</td>
<td>-4.91722</td>
</tr>
</tbody>
</table>
Figure 8: Simulated heat from main condenser compared to data from ENA database

Figure 9: Simulated heat from flue gas condenser compared to data from ENA database
6 Conclusions/Discussion

6.1 Flue gas Condensation Unit

The simulated values of the flue gas condenser agree well with data from the database of ENA Energi. Errors of up to 5% in the temperature of the district heating water after the condenser was seen at at 80% load on the boiler and errors about 4% at 90% load, this may due to the following reasons

- No possibility to measure accurately the flue gas flow in the database and compare with the simulated value
- Flue gas temperatures in the database out of the boiler may not accurate
- A fixed fuel moisture content was used in the model
- Possibilities of errors in the measurement of the district heating water temperature

Errors in district water temperature out of the flue gas condenser can be seen to have the most effect on the heat recovered. A 1°C error in the temperature of the district heating water corresponds to about 10% error in the heat recovered as can be seen in figure 7.

Based on the simulation it can be inferred that (see Appendix 1), the heat of condensation account for about 60-65% of the total heat recovered from the flue gas. While the heat recovered from cooling of the flue gas to the dew point account for about 25-30% of the energy recovered.

6.2 Complete process plant Simulation

On completion of the flue gas condenser model, the model was coupled to the boiler and turbine models with some adjusted. It was however not possible to regulate the load from minimum to maximum because the turbine model is not flexible as it was designed for diagnostic purposes.
The complete model was simulated and validated at four-load points as was done for the flue gas condenser. The results of the simulations obtained showed good agreement with the values from ENA database. It is however only possible to regulate the load 70% to 100% of the nominal load.

The errors observed at the 80% load can be accounted for by an inherited error in the temperature of the district heating water after the flue gas condenser, which may be due to incorrect flue gas temperature or moisture content in the fuel. Small errors in the district water temperature after the condenser can lead to significant errors in the values of heat recovered results obtained from the model.

### 6.3 Achieved Goals

A major achievement of this study is the development of a simulator based model of the ENA process plant with respect to the real plant. Simulations with the model showed that it can be adapted to varying operational demand as may be required and can be used as predictive tool for production planning as well as for investigating the effect of changes in the process.
7 Future Work

Since the turbine model was develop for diagnostic purposes it was impossible to regulate the boiler load below 70% nominal load without experiencing failure in the model simulation. A further tuning of the turbine model is required to make it possible to regulate the boiler to minimum load.

Verification and validation of the model using more accurate measurements for example from commissioning test data would be appropriate in acertaining the accuracy of the model.

Pressure drop over the condenser was set as a constant in the model. It will be interesting to model the pressure drop with respect to variation in atmospheric pressure.
8 References


Daniel Häggestål, Erik Dahlquist (Evaluation of Prosim and IPSEpro, Two Heat and Mass Balance Simulation Softwares), 2003

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Lars Wester, Förbrännings- och rökgasreningsteknik, Kompendium Mälardalens högskola, Institutionen för Samhällsteknik, 2002


Perz, E., 1990, ASME Paper IGTI GT-351, 8P.

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Internet Sources

( www.enae.se , Accessed on 2007-04-12)


( www.simtechnology.com ), Accessed 2007-02-21)
APPENDIX

APPENDIX A: Fuel composition

![Fuel Composition Table]

Usman, Musibau
# Flue Gas Condenser Model Equations

## Mass and Energy balance district heating water

f1a: \( DH_{\text{in.}} \cdot \text{mass} = DH_{\text{out.}} \cdot \text{mass} \);

f2a: \( DH_{\text{out.}} \cdot \text{mass} \cdot DH_{\text{out.}} \cdot h - DH_{\text{in.}} \cdot \text{mass} \cdot DH_{\text{in.}} \cdot h = q_{\text{trans}} \);

f3a: \( DH_{\text{in.}} \cdot p - \text{delta}_p \cdot DH = DH_{\text{out.}} \cdot p \);

## Mass and Energy balance Flue Gas

f1: \( FG_{\text{in.}} \cdot \text{mass} - Vc \cdot \text{mass} = FG_{\text{out.}} \cdot \text{mass} \);

f3: \( FG_{\text{in.}} \cdot p - \text{delta}_p \cdot FG = FG_{\text{out.}} \cdot p \);

## Molar flow of flue gas into the Condenser (mol/Kgflue)

\( fg = \frac{FG_{\text{in.}} \cdot \text{mass}}{\text{fuel}_\text{flow}} \cdot (\frac{FG_{\text{in.}} \cdot \text{Composition.CO2}}{0.0440098} + \frac{FG_{\text{in.}} \cdot \text{Composition.H2O}}{0.0180152} + \frac{FG_{\text{in.}} \cdot \text{Composition.O2}}{0.0319988} + \frac{FG_{\text{in.}} \cdot \text{Composition.N2}}{0.0280134} + \frac{FG_{\text{in.}} \cdot \text{Composition.SO2}}{0.0640588} + \frac{FG_{\text{in.}} \cdot \text{Composition.AR}}{0.0399480}) \);

## Molar flow of dry flue gas out of the Condenser:

\( fg_d = \frac{FG_{\text{in.}} \cdot \text{mass}}{\text{fuel}_\text{flow}} \cdot (\frac{FG_{\text{in.}} \cdot \text{Composition.CO2}}{0.0440098} + \frac{FG_{\text{in.}} \cdot \text{Composition.O2}}{0.0319988} + \frac{FG_{\text{in.}} \cdot \text{Composition.N2}}{0.0280134} + \frac{FG_{\text{in.}} \cdot \text{Composition.SO2}}{0.0640588} + \frac{FG_{\text{in.}} \cdot \text{Composition.AR}}{0.0399480}) \);

## Molar mass of flue gas (Kgflue/mol)

\( f_{\text{MWfluegas}} = \frac{1}{(\frac{FG_{\text{in.}} \cdot \text{Composition.CO2}}{0.0440098} + \frac{FG_{\text{in.}} \cdot \text{Composition.H2O}}{0.0180152} + \frac{FG_{\text{in.}} \cdot \text{Composition.O2}}{0.0319988} + \frac{FG_{\text{in.}} \cdot \text{Composition.N2}}{0.0280134} + \frac{FG_{\text{in.}} \cdot \text{Composition.SO2}}{0.0640588} + \frac{FG_{\text{in.}} \cdot \text{Composition.AR}}{0.0399480})) \);

## Water vapour in Flue gas mol/kgfuel

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\[ \text{f\textsubscript{FG\textsubscript{H2O}}} : \quad \text{FG\textsubscript{H2O}} = (\text{FGin.Composition.H2O}/0.0180152) \times \text{FGin.mass}/\text{fuel\_flow}; \]

# Partial pressure of water vapour in flue gas

\[ \text{f7:} \quad p_{\text{H2O}} = ((\text{FGin.p} + \text{FGout.p})/2) \times ((\text{FGin.Composition.H2O}/0.0180152) \times (\text{FGin.mass}/\text{fuel\_flow})/g); \]

# Estimating Dew Point

\[ \text{f8:} \quad T_{\text{dew}} = ((\ln(p_{\text{H2O}} \times 100000/610.78) \times 238.3)/(17.294-(\ln(p_{\text{H2O}} \times 100000/610.78))); \]

# Sensible heat recovered from cooling Flue gas to dew point

\[ \text{f10:} \quad P1 = \text{fuel\_flow} \times g \times (\text{FGin.Composition.fhpt(FGin.p,FGin.t)} - \text{FGin.Composition.fhpt(FGin.p,Tdew)}) \times \text{MWfluegas}; \]

# Estimating the saturation vapour pressure at the exit temperature

\[ \text{fVp:} \quad Vc.p = (610 \times \exp(\text{FGout.t}/(\text{FGout.t}+238.3) \times 17.2694))/1E+5; \]
\[ \text{fVc:} \quad Vc.mass = \text{FGH2Ocond} \times 0.0180152 \times \text{fuel\_flow}; \]
\[ \text{fVch:} \quad Vc.h = Vc.Composition.fhpx(Vc.p,0); \]

# Estimate remaining water vapor in flue gas at exit temperature

\[ \text{fFG\textsubscript{H2Oout}} : \quad \text{FGH2Oout} = (\text{Vc.p} \times \text{gd})/(((\text{FGin.p} + \text{FGout.p})/2) - \text{Vc.p}); \]

# Condensed water vapor (mol/Kgfuel)

\[ \text{f11a:} \quad \text{FGH2Ocond} = (\text{FGin.Composition.H2O}/0.0180152) \times \text{FGin.mass}/\text{fuel\_flow} – \]
\[ \text{FGH2Oout}; \]

# Heat of Condensation Recovered

\[ \text{f12:} \quad P2 = \text{fuel\_flow} \times \text{FGH2Ocond} \times (-2.4312*((\text{Tdew} + \text{FGout.t})/2) + 2503.4)*0.0180512; \]

# Heat released from cooling uncondensed vapour and dry flue gas

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f14: \[ P_3 = \text{fuel\_flow} \times (\text{gd} + \text{FG}_{\text{H2O}_{\text{out}}} + \text{FG}_{\text{H2O}_{\text{cond}}})/2) \times (\text{FGin} \cdot \text{Composition} \cdot \text{fhpt}((\text{FGin}.p + \text{FGout}.p)/2, \text{Tdew}) - \text{FGout} \cdot \text{Composition} \cdot \text{fhpt}((\text{FGout}.p + \text{FGin}.p)/2, \text{FGout}.t)) \times \text{MW}_{\text{fluegas}}; \]

# Heat released by Cooling of condensed water

f15: \[ P_4 = \text{fuel\_flow} \times (\text{FG}_{\text{H2O}_{\text{in}}} - \text{FG}_{\text{H2O}_{\text{out}}})/2 \times ((2820 + 11.82 \times (\text{FGout}.t + 273.13) - 0.03502 \times (\text{FGout}.t + 273.13)^2 + 0.00003599 \times (\text{FGout}.t + 273.13)^3)/1000) \times 0.0180152 \times (\text{Tdew} - \text{FGout}.t); \]

# Total heat released from flue gas gas

f16: \[ q_{\text{trans}} = y \times (P_1 + P_2 + P_3 + P_4); \]

# Temperature differences

# Type == counter_current then

f7_counter: \[ dt_{\text{in}} = \text{FGin}.t - \text{DHout}.t; \]
f8_counter: \[ dt_{\text{out}} = \text{FGout}.t - \text{DHin}.t; \]

# Logarithmic temperature difference

fUA: \[ htc_{\text{area}} = (-7E-07 \times q_{\text{trans}}^2 + 0.0341 \times q_{\text{trans}} + 64.638); \]
f9: \[ \text{if abs}(dt_{\text{in}}/dt_{\text{out}}) >= 1.2 \text{ || abs}(dt_{\text{out}}/dt_{\text{in}}) >= 1.2 \text{ then} \]

\[ q_{\text{trans}} \times \ln(dt_{\text{in}}/dt_{\text{out}})/(dt_{\text{in}}-dt_{\text{out}}) = htc_{\text{area}}; \]

Else \[ q_{\text{trans}} \times 2.0/(dt_{\text{in}}+dt_{\text{out}}) = htc_{\text{area}}; \]

# Equations describing composition of exit flue gas from condenser

fWATER: \[ \text{FGout} \cdot \text{Composition} \cdot \text{WATER} \times \text{FGout}.mass = 0.0; \]

# no WATER (everything must be H2O)

fAR: \[ \text{FGout} \cdot \text{Composition} \cdot \text{AR} \times \text{FGout}.mass = \text{FGin} \cdot \text{Composition} \cdot \text{AR} \times \text{FGin}.mass; \]
fC2H6: \[ \text{FGout} \cdot \text{Composition} \cdot \text{C2H6} \times \text{FGout}.mass = 0.0; \]
fC3H8: \[ \text{FGout} \cdot \text{Composition} \cdot \text{C3H8} \times \text{FGout}.mass = 0.0; \]
fCH4: \[ \text{FGout} \cdot \text{Composition} \cdot \text{CH4} \times \text{FGout}.mass = 0.0; \]
fCO: \[ \text{FGout} \cdot \text{Composition} \cdot \text{CO} \times \text{FGout}.mass = 0.0; \]

#FCO2: \[ \text{FGout} \cdot \text{Composition} \cdot \text{CO2} \times \text{FGout}.mass = \text{FGin} \cdot \text{Composition} \cdot \text{CO2} \times \text{FGin}.mass; \]

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\[ f_{H2} \text{: } \text{FGout.Composition.H2} = 0.0; \]
\[ f_{H2O} \text{: } \text{FGout.Composition.H2O} \times \text{FGout.mass} = \text{FGin.Composition.H2O} \times \text{FGin.mass} - \frac{\text{FGH2Ocond} \times 0.0180152 \times \text{fuel_flow}}{}; \]
\[ f_{H2S} \text{: } \text{FGout.Composition.H2S} = 0.0; \]
\[ f_{N2} \text{: } \text{FGout.Composition.N2} \times \text{FGout.mass} = \text{FGin.Composition.N2} \times \text{FGin.mass}; \]
\[ f_{O2} \text{: } \text{FGout.Composition.O2} \times \text{FGout.mass} = \text{FGin.Composition.O2} \times \text{FGin.mass}; \]
\[ f_{SO2} \text{: } \text{FGout.Composition.SO2} \times \text{FGout.mass} = \text{FGin.Composition.SO2} \times \text{FGin.mass}; \]
**APPENDIX C: Result Box From PSE for Flue Gas Condenser**

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<th>Model</th>
<th>Value</th>
<th>Unit</th>
<th>Set</th>
<th>Estimate</th>
<th>Limit</th>
<th>Update</th>
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<td>$q_{\text{trans}}$</td>
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</table>

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