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MASTER'S THESIS

MODEL DEVELOPMENT FOR CIRCULATING FLUIDIZED BED BOILER OPERATION

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ABSTRACT

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Model development for circulating fluidized bed boiler operation

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Comprehensive understanding of the heat transfer processes that take place during circulating fluidized bed (CFB) combustion is one of the most important issues in CFB technology development. This leads to possibility of predicting, evaluation and proper design of combustion and heat transfer mechanisms. The aim of this thesis is to develop a model for circulating fluidized bed boiler operation. Empirical correlations are used for determining heat transfer coefficients in each part of the furnace. The proposed model is used both in design and off-design conditions. During off-design simulations fuel moisture content and boiler load effects on boiler operation have been investigated.

In theoretical part of the thesis, fuel properties of most typical classes of biomass are widely reviewed. Various schemes of biomass utilization are presented and, especially, concerning circulating fluidized bed boilers. In addition, possible negative effects of biomass usage in boilers are briefly discussed.

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ABBREVIATIONS

BFB	Bubbling fluidized bed
CCA	Copper-chromium-arsenate
CFB	Circulating fluidized bed
CHP	Combined heat and power
d	Dry mass
DSH	Desuperheater
ESP	Electrostatic precipitator
FB	Fluidized bed
FT	Fluid temperature
GHG	Greenhouse gas emissions
HHV	Higher heating value
HT	Hemispherical temperature
HTU	Hydro-thermal upgrading
INTREX	Integral Recycling Heat Exchanger
IT	Initial deformation temperature
LHV	Lower heating value
MDK	Model Development Kit
MDL	Model description language
PCF	Pulverized coal fired
PCP	Pentachlorophenol
PSE	Process Simulation Environment
RDF	Refuse derived fuel
REF	Recycled refuse fuel
RES	Renewable energy sources
SH	Superheater
SNCR	Selective Non Catalytic Reduction
ST	Softening temperature
Wt	Mass fraction

LIST OF SYMBOLS

a	decay coefficient in splash zone $\left[\frac{1}{m}\right]$
A	heat transfer area $[m^2]$
c	experimentally found coefficient $\left[\frac{1}{m}\right]$
f	time averaged fractional area of the wall covered by solids $[m^2]$
h_d	height above air distributor $[m]$
$\mathrm{h_{out}}$	outer heat transfer coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$\mathrm{H_d}$	hydrogen percentage of the dry sample $[-]$
$\mathrm{HHV_d}$	higher heating value of the dry sample $\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right]$
$h_{hot\ in}$	inlet enthalpy of gas-solid suspension $\left[\frac{kJ}{kg}\right]$
$h_{hot\ out}$	outlet enthalpy of gas-solid suspension $\left[\frac{kJ}{kg}\right]$
$h_{cold_{out}}$	outlet enthalpy of heated fluid in tubes $\left[\frac{kJ}{kg}\right]$
$\mathrm{h_{c,cluster}}$	cluster convective heat transfer coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$\mathrm{h_{c,dilute}}$	dilute convective heat transfer coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$\mathrm{h_{r,cluster}}$	cluster radiative heat transfer coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$\mathrm{h_{r,dilute}}$	dilute radiative heat transfer coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$\mathrm{H_t}$	total height of furnace $[m]$
$Hexit$	height (above air distributor) of centre of gas outlet $[m]$
Hx	height of bottom bed $[m]$
$\mathrm{h_{total}}$	time averaged total heat transfer coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$h_{cold\,\mathrm{in}}$	inlet enthalpy of heated fluid in tubes $\left[\frac{kJ}{kg}\right]$

h_g	heat transfer coefficient due to gas convection $\left[\frac{W}{m^2 \cdot K}\right]$
h_p	heat transfer coefficient due to particle convection $\left[\frac{W}{m^2 \cdot K}\right]$
h_r	heat transfer coefficient due to thermal radiation $\left[\frac{W}{m^2 \cdot K}\right]$
K	decay coefficient in transport zone $\left[\frac{1}{m}\right]$
L	length of separate wall $[m]$
$\mathrm{LHV_d}$	lower heating value of the dry sample $\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right]$
m	mass of gas-solid suspension $[kg]$
$mySolid$	mass fraction of solids $[-]$
m_g	mass of gas phase $[kg]$
m_{hot}	mass flow of gas-solid suspension $\left[\frac{kg}{s}\right]$
m_{cold}	mass flow of heated fluid in tubes $\left[\frac{kg}{s}\right]$
m_s	mass of solid phase $[kg]$
Nu	Nusselt number $[-]$
s	thickness of separating surface$[m]$
q_{trans}	transferred heat $[kW]$
$\mathrm{Re_t}$	Reynolds number based on bed diameter $[-]$
$(T_1 - T_2)$	temperature difference $[K]$
$\mathrm{T_{refr}}$	surface temperature of refractory $[\mathrm{°C}]$
$\mathrm{T_{susp}}$	suspension temperature $[\mathrm{K}]$
$T_{\infty,1}$	temperature of hot media $[K]$
$T_{\infty,2}$	temperature of heated media $[K]$
T_f	average gas temperature in the furnace $[K]$

$T_{s,1}$	surface temperature from the sight of the hot media $[K]$
$T_{s,2}$	surface temperature from the sight of the heated media $[K]$
T_w	water wall surface temperature $[K]$
u_0	superficial gas velocity $\left[\frac{m}{s}\right]$
u_t	terminal gas velocity $\left[\frac{m}{s}\right]$

Greek letters

α_c	heat transfer coefficient of media $\left[\frac{W}{m^2 \cdot K}\right]$
ε_b	equivalent emissivity of the bed $[-]$
ε_f	emissivity of the flame $[-]$
ε_{fw}	view factor between flame and water walls $[-]$
ε_w	emissivity of the wall $[-]$
λ	thermal conductivity of material $\left[\frac{W}{m \cdot K}\right]$
σ	Stefan-Boltzmann constant $\left[\frac{W}{m^2 \cdot K^4}\right]$
$\rho_{2,Hx}$	solids concentration at upper position of bottom bed $\left[\frac{kg}{m^3}\right]$
$\rho_{s,exit}$	solids concentration at gas exit $\left[\frac{kg}{m^3}\right]$
ρ_b	cross-section average bed density $\left[\frac{kg}{m^3}\right]$
ρ_g	gas phase density $\left[\frac{kg}{m^3}\right]$
$\rho_{s,Hx}$	solids concentration at the top of bottom bed $\left[\frac{kg}{m^3}\right]$
ρ_s	average suspension density $\left[\frac{kg}{m^3}\right]$
ρ_{sol}	solid phase density $\left[\frac{kg}{m^3}\right]$

ΔS_{ref}	thickness of refractory layer $[m]$
Φ_{cd}	heat flux due to conduction $[W]$
Φ_{cv}	heat flux due to convection $[W]$
Φ_{r}	heat flux due to thermal radiation $[W]$

1 INTRODUCTION

Climate change and greenhouse gas emissions are seen as present dominant environmental problems. The importance increases due to the difficulty of controlling provoking processes and mitigation of harmful effects. Moreover, the recognition of natural resources limitation and sequential accelerating growth of prices on fossil fuels are significant factors that have strong influence on human activities and way of development in various spheres. At the same time, irregular distribution of fossil fuels reserves results rather strong dependence of many countries on energy imports.

As a result of aforementioned facts, the importance of various alternative types of energy resources is considerable increasing. It is evident that conventional types of fuels will be hardly based the future world's energy markets. There are plenty amount of technologies that permit generation of essential energy in the environmental-friendly way: solar energy, wind energy, bioenergy, geothermal, etc. These technologies utilize such sources of energy that do not harm environment and, as usual, have unlimited reserves.

Bioenergy represents an outstanding opportunity of worldwide utilization of huge biomass potential. Biomass materials may rather efficient substitute for fossil fuels in various applications. Among the most important biomass benefits are the global wide spreading and carbon-neutral nature of feedstock.

The way of biomass conversion into useful energy depends on different factors, such as biomass type, feedstock availability, and end-use application. It is possible to get three main products from biomass material are heat, power and transport fuels. Continues progress of biomass technologies increases their competitiveness and efficiency.

Biomass combustion and co-firing are the most accepted methods for converting biomass energy into heat or electricity. There are different schemes, and each scheme has its benefits and drawbacks. One of the most promising and reliable technology is fluidized bed combustion. Among two main variations of fluidized bed boilers, circulating fluidized bed combustion attracts a significant attention due to diversified advantages of it.

In order to get clear picture of specific processes that take place during biomass combustion, various models are created. This permits predicting future results and possible effects of various actions. In fact, the majority of available data in this field is connected with laboratory-scale modules. There is a little amount of experiment data on heat transfer processes in large-scale units, and results obtained in laboratory units cannot always been applied to boiler design. Such situation has its premises: the difficulty of obtaining data from commercial operating boilers, complication of monitoring and description processes that are taking place in the furnace.

This work concentrates on modeling of the processes that occur during combustion in circulating fluidized bed boiler. The model of the boiler is designed in IPSEpro software. Moreover, biomass properties and boiler operations are reviewed. The aim of the present work is creation of model with reasonable level of complication. In order to maintain the reasonable level of model complexity, several simplifications are assumed. These simplifications are applying to heat transfer processes and hydrodynamic model at the furnace volume.

The developed model may be used for simulation various off-design work conditions of the boiler. In present work, results of two simulations are presented. First simulation constitutes of fuel moisture variations modeling and observation of resulted effects. Second simulation represents the result of boiler load variations. Both simulations have high level of importance for boiler operation due to spreading of examined effects and significance of monitoring parameters.

2 BIOENERGY OVERVIEW

Energy resources can be commonly classified into two groups:

- Non-renewable resources of energy
- Renewable energy sources (RES)

Non-renewable resources cannot be renewed in such manner that current level of usage is preserved. Fossil fuels (like coal, oil and natural gas) and nuclear power are represented examples of non-renewable resources. These resources are represented in limited amount and by its nature it demands huge amount of time for regeneration.

The major part of actual industrial and other human activities is based on utilization of non-renewable resources. This situation leads to some serious shortcomings. Firstly, it results energy dependence on energy resources supplier in a case of lack of own fossil fuels' reserves. Secondly, gradual decreasing of worldwide stocks of oil, coal and gas leads to consequential growth of fossil fuels prices. Thirdly, high level of industrial activities based on the fossil fuels usage results various types of pollution that often irreversibly harm environment.

Simultaneously, there is wide amount of available renewable resources of energy that can be progressively or in a short period of time renewed. Renewable resources of energy are represented by bioenergy, wind energy, hydro energy, tidal energy, geothermal energy, etc. RES are non-polluting although technologies that used for generation useful energy from them may cause some impacts to environment. In addition, the availability and cost-efficiency are highly varied for different types of renewable energy sources.

Bioenergy gives an outstanding opportunity to overcome the most important world's challenges – climate change and energy security. In general, bioenergy is energy produced from biomass. Biomass is represented by organic materials grown, collected or harvested for energy use. It is a source of renewable hydrocarbons that can be converted to provide energy carriers (heat, electricity and transport fuels) as well as materials and chemicals (IEA, 2008).

Biomass is a worldwide abundant renewable source of energy. Today bioenergy represents the largest contributor for energy supplying among utilized renewable sources of energy. Bioenergy provides around 10 - 15 percent (or 45 ± 10 EJ) of the world's final energy consumption (Khan et al., 2009). Traditional usage of biomass, as for cooking and heating, is the most common biomass utilization, and applied especially in developing countries. Level of bioenergy share in energy consumption in the industrialized countries varies and, it is typically around 9 – 14 percent (Hall et al., 1993).

Biomass can be divided into the following groups:

- Woody biomass
- Herbaceous biomass

- Waste

Biomass has a rather high potential and proper activities will lead to prospective energy security and reliability. The potential is vary for different regions and for different types of biomass.

Global technical biomass potential from selected residues: ~ 30 EJ. Technical potential of residues in different regions is presented in Figure 2.1. Forestry biomass potential is estimated in limits of 29 - 45 EJ. Potential of energy crops is strongly influenced by international and national environmental strategies and agreements associated with food security and environment. In fact, the evaluation of biomass potentials is a quite approximate due to its high dependence on upcoming food and feedstock requirements that are driven by various factors. Most important factors among them are the following: level of population growth, developing of technologies for agriculture and biomass production and rate of climate changes. (Thrän, 2010)

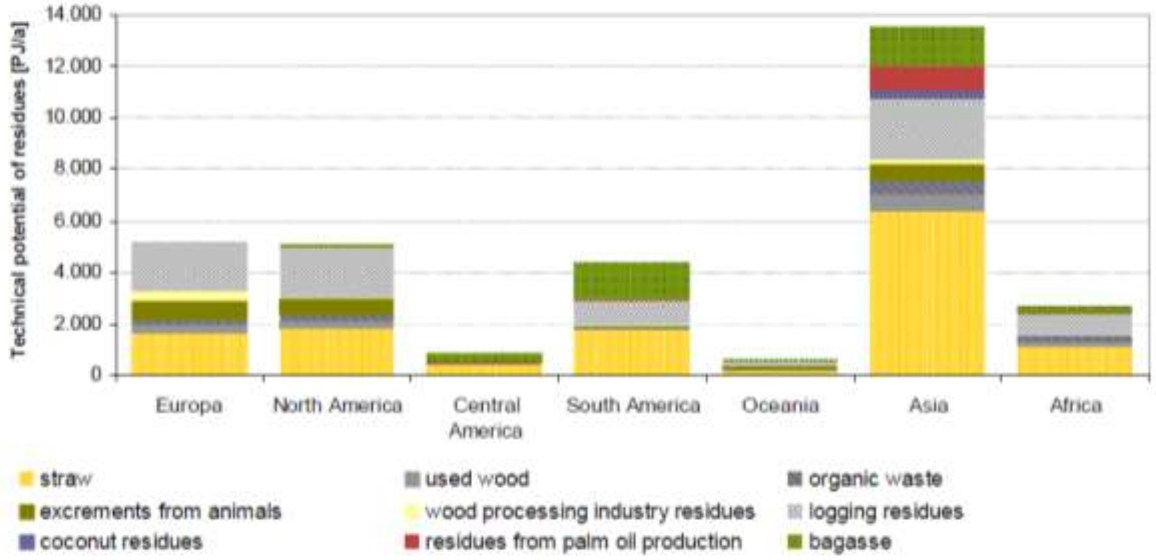


Figure 2.1. Global technical biomass potential from selected residues (Thrän, 2010)

It should be noted that implementation of bioenergy possibilities in case of improper management may result significant environmental harm. At the same time, in the event that all risks will be considered and avoided, bioenergy allows reaching significant results of sustainability.

The total impacts of any technology should be evaluated during life-cycle period. Most constitutive factors that shaped bioenergy impacts are the following: changes appeared to the state of utilized land resources (level of utilization, application of fertilizers, etc.), choice of source and rate of management, and also way of processing biomass feedstock into useful energy or material. Improper management may lead to various environmental problems, as for instance decreasing of biodiversity, soil depletion and erosion. The realization of bioenergy potential with an adequate technique enables to avoid many drawbacks caused by utilization of fossil fuels. The main task is to achieve high results simultaneously with the preserving natural ecosystems.

Bioenergy makes it possible to decrease level of emissions in power and heat generation and transport activities. One of the main benefits towards biomass fuels is their carbon-neutrality during their life-cycle. Whole carbon that the plant accumulates during the growing stage is emitted during its treatment. At the same time, improper actions may cause significant damages for the environment during processing. For instance, replacing forest area with the fields of energy crops will damage local natural system for a long time.

The sphere of liquid biofuels attracts increasing attention. Liquid biofuels enable to decrease greenhouse gas emissions (GHG) level in transport sector. However, existing shortcomings of first-generation biofuels cause some anxiety. The production of first-generation biofuels from food crops can possibly affects on food production rate, and the prices are relatively high yet. On the contrary, development of second-generation biofuels allows gaining advantageous results in the future. The main benefit of this type of biofuels is its origin from non-food crops that can help to secure food production and also expand feedstock’s possibilities.

In addition to environmental benefits, bioenergy development permits to achieve valuable results in economical and social aspects. Intensive research, development and subsequent implementation permit creation of new work places and possibilities for business and entrepreneurship. Furthermore, possible utilization of local energy resources leads to economical benefits that contribute to economical sustainability. On the other hand, the implementation of bioenergy usually requires assistance from the government due to not sufficient level of current development. Continuous progress in technology will lead to increasing of its competitiveness and attractiveness for all stakeholders, as for instance government, producers, and consumers.

3 BIOMASS FUELS

Biomass sources can be utilized in various applications, as for instance heat and power generation, gasification, producing of liquid biofuels. Each type of biomass has properties different from other. The whole scope of these properties defines more and less acceptable technologies in each particular case. The difference in characteristics between biomass and fossil fuel should be taken into consideration. The effect of fossil fuels substitution in frames of existing technologies should be evaluated in order to avoid problems and breakdowns. Types and characteristics of woody and herbaceous biomass will be discussed further.

3.1 Woody biomass

3.1.1 Types of woody biomass

Wood has been widely utilized by mankind for many centuries. It was broadly spread type of fuel both in traditional and industrial ways of utilization before the coal became a dominant fuel in industry. At the same time during the last half of the 20th century the wood consumption in countries with high forest area has been increasing. Such countries as Finland, Sweden and the USA are taking advantage from their forest resources in order to achieve high reliability in energy supplying and utilization of local resources. (Fagernäs et al., 2006)

It is possible to divide woody biomass by its origin into groups:

- Logging residues
- Industrial by-products
- Urban wood waste

Variations of common woody residues from different processes are presented in Table 3.1. (FAO, 1990).

Table 3.1. Sources and types of woody residue

Source of residue	Type of residue
Forest operations	Branches, needles, leaves, stumps, roots, low-grade and decayed wood, slashings and sawdust

Sawmilling and planing	Bark, sawdust, trimmings, split wood, planer shavings
Plywood production	Bark, core, sawdust, veneer clippings and waste, panel trim, sanderdust
Particleboard production	Bark, screening fines, panel trim, sawdust, sanderdust

Logging residues are produced during general harvesting procedures of woody industry: stumps, from final fellings, etc. In general, about 66 percent of wood is removed from the forest for sequential treatment, and the rest of woody material is left on-site, burn on-site or utilized as wood fuel for firewood or wood chips (FAO, 1976). In spite of the fact that wide amount of available woody biomass is stayed in the forest area, the processing it further is not usually reasonable. As the matter of fact, the expenses on collecting, handling, transportation and following processing may appear rather high. Simultaneously, soil quality should not suffer from the lack of nutrient due to residue removal. To secure soil quality proper amount of residues can be retained in the forest area or ash recycling technologies can be implemented. Transportation costs have marginal influence on economical reasonability of logging residues handling due to low energy and bulk density of material. Location for converting woody raw materials into more acceptable form for transportation (chipping, for instance) should be properly considered from economical point. Usually chipping on-site is favourable in a case of transportation over long distances of significant amounts of residues.

Industrial by-products are generated in various industries connected with wood materials processing: processing of timber, plywood and veneer mills, various pulp mills, and particleboard plants. The appeared residues, such as sawdust, bark, sander dust, are usually qualified as “hog fuel”. This definition is applied because of major part of this woody material is processed through hammer mills that also known as “hammer hogs” or “hogs”. (Miller, 2008)

Quantities of woody residue vary for different industries. The sawmilling and plywood sectors result around 40 - 55 percent of residue from their incoming raw material. This amount may be utilized and satisfactory cover an energy demands of these industries. At the same time, such industries as particleboard manufacturing produce a little amount of waste –

5-10 percent from incoming round wood. In order to increase overall efficiency of wood processing the integrated schemes may be succeeding. (FAO, 1990)

The category of industrial by-products includes also woody waste from secondary processing industries such as furniture, flooring, and related product manufacturing operations. Pulp and paper sector produces some particular residues: black liquor from kraft mills and red liquor from sulfite mills. These types of residue can be utilized in special chemical recovery boilers that ensure the returning of sodium and sulphur to the Kraft process and provide steam. (Fagernäs et al., 2006)

Finally, it is possible to allocate the category of urban wood waste. Some examples of residue types that compose this category are construction, demolition, and land-clearing materials; wood from pallet processors; manufacturing residues (for instance, from the production of manufactured homes). Treated wood wastes are also can be successfully utilized. Among these wastes are used railroad ties, used utility poles, lumber treated with copper-chromium-arsenate (CCA) or pentachlorophenol (PCP) for outdoor applications, and related products. Such materials are reprocessed separately from untreated wood residues. (Fagernäs et al., 2006)

3.1.2 Characteristics of woody biomass

Chemical and physical characteristics of woody biomass define appropriate technologies and vary a lot for different categories. Woody biomass, either gymnosperms (softwoods) or angiosperms (hardwoods), is inherently anisotropic and hygroscopic; it is a porous material, with the porosity caused by the hollow fibres that make up the woody material. Wood is formed from cellulose, the hemicelluloses, one or another type of lignin, and extractives such as pinoresinol, catechin, and other related chemical compounds. (Fagernäs et al., 2006)

Solid wood usually has an average specific gravity of 0.4 - 0.7. Table 3.2 represents an overview of specific gravities for some types of wood. (Bergman et al., 2010) This value for fast-growing types of woody biomass is usually lower then for naturally grown trees.

Table 3.2. Specific gravities for selected species (dry basis)

Species	Specific Gravity
Pitch Pine	0.47–0.52
White Pine	0.34–0.35
White Oak	0.60–0.68
Willow	0.56–0.69

Moisture content is rather important characteristic for all kind of fuels due to its influence on processes of treatment. This property influences on many physical and mechanical properties. Moreover, moisture determines an amount of heat that is absorbed by fuel in a drying stage of processing. The level of this parameter is a function of growing process of wood and, in addition, pretreatment processes. The logging residues are keeping during fixed period of time on the harvesting area and, as a result, moisture content increases. Since the equipment that utilized in sawmilling and other woody industries often water-cooled, the major part of moisture in sawdust is appeared during pretreatment activities. Sawdust and "hog fuel" are usually delivered to boilers with the moisture content of 40 – 50 percent (Prinzing, 1996). Heartwood in the hardwood is commonly in a range of 32 – 48 percent moisture. For softwood this characteristic is around 52 – 71 percent (Haygreen, 1990).

The value of moisture content is usually evaluated as:

$$(\text{moisture content}) = \frac{(\text{moisture weight})}{(\text{total weight})} 100[\%] \tag{3.1}$$

Bulk density is rather important parameter for handling and conveying systems. It determines by values of moisture and specific gravity. Typical bulk density for fuels with high moisture content, such as sawdust and "hog fuel", is around 0.205 – 0.256 kg/m^3. Fuels with lower moisture parameter, as for instance shavings or pallet wastes with moisture around 12 percent, has bulk density in limits of 0.128 – 0.154 kg/m^3. (Prinzing, 1996)

3.1.3 Proximate and ultimate analyses of woody biomass

Proximate and ultimate analyses are two basic analyses for comprehensive consideration about chemical fuel composition. The proximate analysis determines such characteristics as moisture, ash content, fixed carbon and volatile matter. The ultimate analysis defines values for carbon, hydrogen, nitrogen, sulphur, chlorine, and oxygen as a percentage of the dry fuel weight.

Moisture is strongly important parameter for all kind of fuels. As it was noted before, high moisture content results heat loss due to heating and evaporation of water contained in the fuel.

Fixed carbon and volatile matter also effect on the heating value. Fixed carbon represents a solid matter of the fuel that stayed in the furnace after volatile release. Volatile matters are such gases as methane, hydrocarbons, hydrogen, carbon monoxide, and carbon dioxide. High volatile matter indicates of easy fuel ignition.

Ash refers to non-combustible matter in the fuel. Ash content of the fuel is significant value for proper design and activities connected with combustion process and ash handling. For biomass fuel this parameter has quite important role due to in a case of replacing fossil fuels ash content may cause some challenges (slagging and fouling).

Chemical composition of woody biomass is formed by condition of growing and, additionally, pretreatment practices. Table 3.3 shows proximate and ultimate analyses for some types of woody biomass (Tillman, 2002).

Table 3.3. Proximate and ultimate analyses for selected types of woody biomass

Characteristic	Fuel type			
	Pine	Red Oak	Mixed sawdust	Urban wood waste
Proximate Analysis (dry Wt %)				
Moisture	45.0	28.8	40.0	30.8
Fixed Carbon	15.2	19.0	19.0	18.1
Volatiles	84.7	79.5	80.0	76.0
Ash	0.1	1.5	1.0	5.9
Ultimate Analysis (dry Wt %)				
Carbon	49.1	51.6	49.2	48.0
Hydrogen	6.4	5.8	6.0	5.5
Oxygen	44.0	40.0	43.0	39.1

Nitrogen	0.2	0.5	0.4	1.4
Sulphur	0.2	<0.1	<0.1	0.1
Ash	0.1	1.5	1.0	5.9

3.1.4 Ash composition and properties for woody biomass

Inorganic matter is contained in the fuel and shape the composition of ash. Inorganic fraction contains such chemical compounds as ferrum, magnesium, calcium, oxides SO_4 and CO_3, etc. This parameter is expressed in percent of the total fuel mass or in ratio g/kJ. This value is usually low for woody biomass in comparison with coal. Simultaneously, urban wood waste has higher ash content due to the presence of various impurities. Ash elemental analysis for some samples of woody biomass is presented in Table 3.4 (Tillman, 2002).

Table 3.4. Ash elemental analysis of typical wood fuels

Characteristic	Fuel type		
	Hardwood sawdust	Pine bark	Mixed hard- and softwood
Elemental composition (Wt %)			
SiO_2	23.7	0.40	23.5
Al_2O_3	4.10	0.30	5.10
TiO_2	0.36	0	0.10
Fe_2O_3	1.65	0.20	2.10
CaO	39.9	40.6	33.6
MgO	4.84	5.10	5.10
Na_2O	2.25	0.30	0.20
K_2O	9.81	26.5	12.0
P_2O_5	2.06	11.5	4.80
SO_3	1.86	3.0	1.60
Reducing Ash Fusion Temperatures (°C)			
Initial deformation	1246	1375	1230
Softening	1414	1507	1240
Hemispherical	1417	1506	1245
Fluid	1424	1507	1290
Oxidizing Ash Fusion Temperatures (°C)			
Initial deformation	1397	1340	1210

Softening	1406	1525	1225
Hemispherical	1408	1650	1250
Fluid	1414	1650	1275

Ash properties are rather essential for prediction of its behaviour during fuel combustion. Standard ASTM E1857 – 97 defines four critical temperatures of ash behaviour. Figure 3.1 illustrates critical temperature points for ash. First position represents the view of ash sample before heating. Second position corresponds to the moment of deformation of the sample top. Softening temperature is the temperature when the cone is turned into sphere. Fourth position corresponds to the moment of deformation of the sample into hemisphere. Fluid temperature is the temperature of the cone fusion.

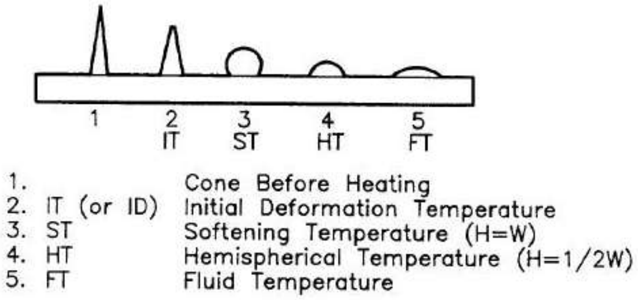


Figure 3.1. Critical temperature points according to ASTM E1857 – 97 standards

Fusibility of ash is determined by its chemical composition and highly response even on minimal changes. Usually fusion temperatures are measured under both reducing and oxidizing conditions. Table 3.4 illustrates ash fusion temperatures for selected types of woody biomass.

3.1.5 Heating value of woody biomass

Heating value is a significant parameter that characterizes the fuel quality. It indicates an amount of fuel that should be burnt to produce a given quantity of energy. This value is highly depends on various factors that were mentioned before. Usually biomass fuel has lower heating value in comparison with common fossil fuels. Moreover, as a result of harvesting technologies quality of biomass may vary, and these variations should be considered.

Woody biomass, as other types of fuels, consists of carbon, hydrogen and oxygen that result after complete combustion water H_2O and carbon dioxide CO_2. In a case of accounting the latent heat of water vapour heating value is called the higher heating value (HHV), otherwise it is named the lower heating value (LHV).

Table 3.5 represents meanings of HHV for some woody biomass samples (Tillman, 2002).

Table 3.5. Higher heating values for wood fuels

Type of fuel	Pine	Red oak	Mixed Sawdust	Urban Wood Waste
HHV_d, MJ/kg	19.79	18.78	19.56	19.47

Both heating values are connected through equation (Núñez-Regueira et al., 2001):

$$LHV_d = HHV_d - 24.42 \cdot (9 \cdot H_d), \tag{3.2}$$

where LHV_d is the lower heating value of the dry sample $\left[\frac{MJ}{kg}\right]$

HHV_d is the higher heating value of the dry sample $\left[\frac{MJ}{kg}\right]$

H_d is the hydrogen percentage of the dry sample $[-]$

The heat of vaporization of water is taken as $24.42\frac{MJ}{kg}$, and the water formed during combustion is nine times the hydrogen content of the fuel.

3.2 Herbaceous biomass

3.2.1 Types of herbaceous biomass

Another class of biomass fuels is herbaceous biomass. It includes agricultural crops, by-products and residues of crops, and various energy crops.

According to the European solid biofuel standard, classification of herbaceous biomass is the following (Alakangas, 2009):

1. Herbaceous biomass from agriculture and horticulture:
    - Cereal crops
    - Grasses
    - Oil seed crops
    - Root crops

  - Legume crops
  - Flowers
  - Segregated biomass from gardens, parks, etc.
  - Blends and mixtures
2. By-products and residues from herbaceous processing industry:
  - Chemically untreated herbaceous residues
  - Chemically treated herbaceous residues
  - Blends and mixtures
3. Blends and mixtures

Most valuable and widespread crops for bioenergy usage are wheat, rice, maize, and sugarcane. Straw, rice husks, coffee husks, sugarcane waste and other residues may provide quite broad source of renewable energy.

Energy crops are represented by agricultural crops cultivated for energy purposes. Such crops may be perennial, such as reed canary grass, miscanthus, and switchgrass, and short rotation coppices, such as salix. Energy crops represent an attractive possibility for effective energy production.

Cultivation of energy crops for non-food applications is increasing. For example, in Sweden, over 15 000 ha of willow have been cultivated for wood co-firing applications or for biomass CHP and district heat boilers. In Finland, around 16 000 ha of reed canary grass have been cultivated for similar purposes. Level of crop yields is highly influenced by local climate conditions and soil properties. Sum of harvesting and transportation costs is rather significant for determination of cost-competitiveness of technology. It depends on crop type and its properties. In a case of possible utilization of existing agricultural machinery and conventional experience, harvesting expenses could be on relatively low (IEA, 2008).

The most crucial barriers for utilization of herbaceous biomass possibilities are climate, soil quality, and food demand (Fagernäs et al., 2006). Each type of crops is suitable for particular climate conditions. Conclusive climate parameters, such as average temperature and level of rainfall, should be considered. Various climate conditions lead to uneven distribution of various types of biomass resources. Soil quality should be maintained on a given level. To avoid soil depletion, amount of removed residues should not exceed defined level. Moreover, level of fertilization should be acceptable and possibly low. Continuous growth of Earth population results increasing of food demand which requires new areas for cultivation, and that may result challenges for energy crops development and expansion of cultivation area.

Typically, energy utilization of agricultural biomass is represented by straw usage for heating, and applications of animal manure and green crops for biogas production. Simultaneously, potential of herbaceous biomass are rather high. Denmark, China, the USA and numerous of other countries widely utilize this potential for energy production. China takes advantage of available amounts of rice, corn and wheat on its territory and over 40 percent of the biomass energy is generated from these sources (Jianxiong, 2003). While Denmark focuses on straw utilization. Straw has a quite high potential in Europe due to available feedstock. At the same time, it is not always competitive with fossil fuels utilization due to gathering, handling, and logistic issues.

The properties of herbaceous biomass basically differ from woody biomass. Herbaceous biomass produces higher amount of ash in comparison with woody materials. This fact may lead to some problems with slagging and fouling of heat transfer surfaces.

3.2.2 Characteristics of herbaceous biomass

Characteristics of every type of biomass define its possible application, sequential drawbacks and possible benefits. Most important discussed parameters are similar to aforementioned for woody biomass.

Typically, herbaceous biomass has rather low level of bulk density. Various types of biomass have different values that are usually determined by pretreatment activities over biomass material. This parameter highly influences on transportability and cost-efficiency of biomass treatment.

Table 3.6 presents typical bulk densities for some types of herbaceous biomass (Tillman 2002, Rossi 1985).

Table 3.6. Values of bulk densities for herbaceous materials

Material	Bulk density, kg/m^3
Baled switchgrass	102
Cotton gin trash	78
Rice hulls	232
Peanut shells	176
Hybrid corn seed	320

Typical bulk density for coal is around 833 kg/m^3 (Miller, 2008). Hence, bulk density of biomass is lower, and this means that, for achieving the same level of generated energy, bigger amount of material is needed. Such field crops, as switchgrass has density around 64 kg/m^3 in loose form, and in baled form their density increases to 102 kg/m^3 (Tillman, 2002).

Increasing the fuel density is one of crucial moments in development of biomass utilization. Bulk density influences on various parameters: handling and transportation processes, volume of storage area, and on overall cost-efficiency. Briquetting and pelleting processes may be rather beneficial in some cases. Simultaneously, as usual, agricultural residues, due to low bulky density and structure, are resistant to compression and consequently resistant to effective densification (Werther et al., 2000). Moreover, such activities require additional expenses, and acceptability should be calculated and evaluated in every particular case.

3.2.3 Proximate and ultimate analyses of herbaceous biomass

Proximate and ultimate analyses characteristics were discussed before for woody biomass. It should be noted that there are rather high variety of parameters for different types of herbaceous biomass. The values are influenced by nature of biomass feedstock and, additionally, by possible chemical treatment actions on it.

Table 3.7 shows proximate and ultimate analysis for some types of herbaceous biomass (Rossi, 1985).

Table 3.7. Proximate and ultimate analyses for selected types of herbaceous biomass

Characteristic	Fuel type				
	Fresh	Reed	Mulch	Rice	Bagasse

	switchgrass	canary grass	hay	hulls	
Proximate Analysis (dry Wt %)					
Moisture	15	65.2	19.5	7-10	45
Fixed Carbon	16.08	19.8	17.1	15.8	11.95
Volatiles	76.18	76.1	77.6	63.6	86.62
Ash	7.74	4.1	5.3	20.6	2.44
Ultimate Analysis (dry Wt %)					
Carbon	46.73	45.8	46.5	38.3	48.64
Hydrogen	5.88	6.1	5.7	4.36	5.87
Oxygen	38.99	42.9	40.6	35.45	42.82
Nitrogen	0.54	1.0	1.7	0.83	0.16
Sulphur	0.13	0.1	0.2	0.06	0.04
Ash	7.74	4.1	5.3	20.6	2.44

Significant vacillation of properties of herbaceous biomass increases difficulty of it practical application in energy sphere. Moisture content for most agricultural residues is determined in most cases by character of separating process from crop body and has typically comparatively low level. At the same time, it can be noticed from Table 3.7, that some kinds of biomass moisture is rather high, as for instance bagasse and reed canary grass. High moisture may cause decreasing combustion temperature and affect on the whole process of biomass conversion. In order to gain sufficient level of moisture, some drying pre-treatment should be applied.

In comparison with coal, herbaceous biomass has high level of volatiles. It means that this fuel type is more easily to ignite and to combust.

Some harmful elements in content may demand special actions and should be under control. Typical problems appear with high chlorine concentration. This parameter for herbaceous biomass is significantly higher than for woody biomass. Usually level of this value is around 0.08 - 0.16 percent for switchgrass, while rice straw may contain 0.50 percent. Chlorine concentration for field crops is determined by level of fertilizers and also by harvest cycles. Chlorine content may cause some operational problems due to corrosion of the surfaces. Sulphur and nitrogen concentrations are rather important parameters for the processes of biomass utilization. Their levels are determined by the nature of feedstock and level of fertilization. High concentration of harmful elements may lead not only to some operational risks during utilization of biomass material, such as corrosion and slagging, but, moreover, may cause harmful environmental effects. (Miller, 2008)

3.2.4 Ash composition and properties for herbaceous biomass

Ash composition has rather high importance in process of evaluation possible applications for biomass material. As it was mentioned before, ash content is strongly influenced on processes of biomass treatment. High level of ash in the fuel may cause undesirable effects on contacted surfaces and, furthermore, lead to environmental concerns.

Recent years numerous researches have investigated ash composition and behaviour in various applications for herbaceous biomass. This field of knowledge is quite important due to active development of herbaceous biomass utilization. Herbaceous biomass is characterized by relatively high ash content and high alkalinity (K_2O and Na_2O).

Table 3.8 illustrates ash elemental analysis of some samples of herbaceous fuels (Rossi, 1985).

Table 3.8. Ash elemental analysis of some herbaceous fuels

Characteristic	Fuel type			
	Fresh switchgrass	Wheat straw	Rice straw	Alfalfa stems
Elemental composition (Wt %)				
SiO_2	65.18	55.70	73.00	1.44
Al_2O_3	4.51	1.80	1.40	0.60
TiO_2	0.24	0.00	0.00	0.05
Fe_2O_3	2.03	0.70	0.60	0.25
CaO	5.60	2.60	1.90	12.90
MgO	3.00	2.40	1.80	4.24
Na_2O	0.58	0.90	0.40	0.61
K_2O	11.60	22.80	13.50	40.53
P_2O_5	4.50	1.20	1.40	7.67

SO_3	0.44	1.70	0.70	1.60
CO_2	0.00	0.00	0.00	17.44
Base/Acid	0.33	0.51	0.24	28.00

It can be noticed from Table 3.8, that some kinds of biomass has comparatively high level of K_2O. It content is determined by the usage of fertilizers during crops growing. K_2O content affects on ash fusion. The relation is presented in Table 3.9 (Werther et al., 2000). Because of variability of inorganic matter content for reviewed biomass, accurate determination of ash melting temperatures is hardly realized. It is seen from the Table 3.9 that ash fusion temperatures vary for different types of biomass. Consequently, combustion of some biomass material, as for instance wheat and rye straw, may required more sophisticated modifications for the existing plants.

Table 3.9. Ash melting temperatures for straws

Biomass material	Straws			
Characteristics	Wheat	Rye	Oat	Barley
K_2O (wt % in ash)	6.6	19.2	40.3	40.3
Initial deformation temperature (°C)	900-1050	800-850	750-850	730-800
Hemispherical temperature (°C)	1300-1400	1050-1150	1000-1100	850-1050
Fluid temperature (°C)	1400-1500	1300-1400	1150-1250	1050-1200

Agglomeration is one of the major problems during herbaceous biomass combustion in fluidized bed boilers. Bed agglomeration starts when part of fuel ash melts and causes adhesion of bed particles (Bapat et al., 1997).

Ash particles may dispose on the cooling surfaces and furnace walls that will results in slagging and fouling. It is possible roughly estimate the slagging and fouling potential for biomass fuels, basing on ash elemental analysis. As a matter of fact, fuels with relatively low alkali content – below 0.172 kg/GJ- with high probability will not cause problems with slagging and fouling. At the same time, there is rather high expectancy of slagging and fouling in a case of alkalinity level above 0.344 kg/GJ. Table 3.10 represents indices for some herbaceous biomass species. (Miles et al., 1993)

Table 3.10. Slagging and fouling indexes for some types of herbaceous fuels

Biomass fuel	Miles slagging and fouling index (kg/GJ) of K_2O and Na_2O	Deposition propensity
Wheat Straw	1.33	High
Alfalfa Stems	1.45-1.97	High
Reed Canary Grass	0.51	High
Rice Straw	0.78	High
Fresh Switchgrass	0.34-0.52	High

3.2.5 Heating value of herbaceous biomass

Heating value is the value that characterizes energy content of fuel. As it was discussed before, heating value depends on various factors. For instance, moisture content highly affects on the level of extracted energy. Table 3.11 shows higher heating values for some samples of herbaceous biomass (Miles et al. 1995).

Table 3.11. Higher heating values for herbaceous fuels

Type of fuel	Fresh switchgrass	Sugar cane bagasse	Wheat straw	Rice straw	Alfalfa stems
HHV_d, MJ/kg	18.06	18.99	17.94	15.09	18.67

Table 3.11 indicates that typical examples of herbaceous biomass have HHV on the lower level than for the coal, at the same time it is comparable with the level for woody biomass.

4 BIOMASS COMBUSTION

4.1 Biomass conversion technologies

The main technologies for conversion biomass to useful energy are combustion, gasification, combined heat and power (CHP) production, co-firing and production of refined biomass fuels, such as pellets and pyrolysis oil (Fagernäs et al., 2006).

Various factors, such as chemical and physical properties, feedstock availability, and possibility of utilization within existing equipment, determine the capability and ways for biomass conversion.

The main processes of thermo-chemical conversion for biomass are shown in the flowchart in Figure 4.1.

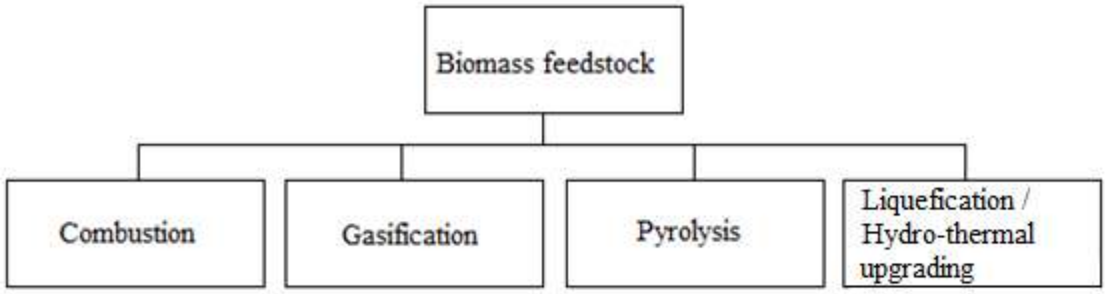


Figure 4.1. Main processes of thermo-chemical conversion for biomass (McKendry, 2002)

Biomass combustion represents rather complicated process of consistent homogeneous and heterogeneous reactions. Process of combustion includes the following stages: drying, devolatilization, gasification, char combustion, and gas phase reactions (Khan et al., 2009). The products of process are hot gases with temperatures around 800 - 1000°C. Biomass feedstock composition and combustion conditions determine structure and properties of flue gases.

Gasification is the process in which an organic matter of biomass material is converted into combustible gases by partial oxidation that can be then utilized in boilers, gas turbines, lime kilns, and other applications (McKendry, 2002). Moreover, this way of conversion may produce synthesis gases from which liquid fuels or chemicals can be generated. In recent years, development and research of gasification technology attract increasing attention, and the implementation of it became more competitive.

Another beneficial thermo-chemical conversion process is pyrolysis. Pyrolysis is the conversion of biomass to liquid (bio-oil or bio-crude), solid and gaseous products by heating the feedstock in the absence of air to the temperature around 500°C. Bio-oil may be used in turbines and engines, and, in addition, it represents a feedstock for biorefineries. (McKendry, 2002) Fast pyrolysis represents the process of thermal decomposition in which the material is thermally cracked using a short vapour residence time in the reaction zone. Pyrolysis oil - the product of fast pyrolysis process – has been estimated as the most inexpensive liquid fuel produced from biomass. (Fagernäs et al. 2006)

Other possible ways for bio-oil production are liquefaction and hydro-thermal upgrading (HTU). These processes are on the pilot stage of development. In HTU processes biomass is reformed in a wet environment at high pressure to partly oxygenated hydrocarbons. The interest in liquefaction is low because the reactors and fuel-feeding systems are more complicated and, as result, expensive in comparison with pyrolysis processes. Liquefaction is the conversion process of biomass into a stable liquid hydrocarbon using low temperatures and high hydrogen pressures. (McKendry, 2002)

4.2 Biomass co-firing

Co-firing represents the simultaneous combustion of two different fuels. The practice of co-combustion biomass fuels and fossil fuel is rather attractive and beneficial. There are different possible compositions of biomass-fossil fuels and various schemes that may be applied. Currently direct biomass co-firing is the most widespread way. Addition of biomass fuel to conventional coal-fired plants is becoming rather popular. In this case biomass feedstock offers a supplementary energy resource, and with proper management and good conditions it will lead to various advantages.

The typical scheme of biomass co-firing is implemented in Finland. It is an application of a fluidized bed combustion technologies within the range 20 to 310 MW where different types of woody residues from the wood industry are co-fired with coal, oil, recycled refuse fuel (REF), refuse derived fuel (RDF). There is high number of grate boilers in the range 1 – 30 MW for district heating purposes. Although small capacity boilers are usually biomass-fired, co-firing of different types of biomass is also applied. Pulp and paper industry utilize various mixtures of bark, woody residues, coal and oil. (Al-Mansour, 2010)

Biomass-firing usually has higher operational costs due to specific features of biomass fuels, as for instance low bulk density and higher transportation costs. As a result, co-firing gives good opportunity for decreasing investment cost and other expenses. Simultaneously, the efficiency of current biomass combustion technologies is lower than for conventional fossil fuel fired applications. The reasons of this are smaller capacity of biomass-fired facilities, more reliable technologies for fossil fuels combustion, etc. As a result, utilization of biomass with coal or other fossil fuels frequently may be beneficial.

Three main co-firing schemes for biomass materials in coal-fired plants are the following:

- Direct co-firing
- Indirect co-firing
- Parallel co-firing

These technologies are illustrated in Figure 4.2.

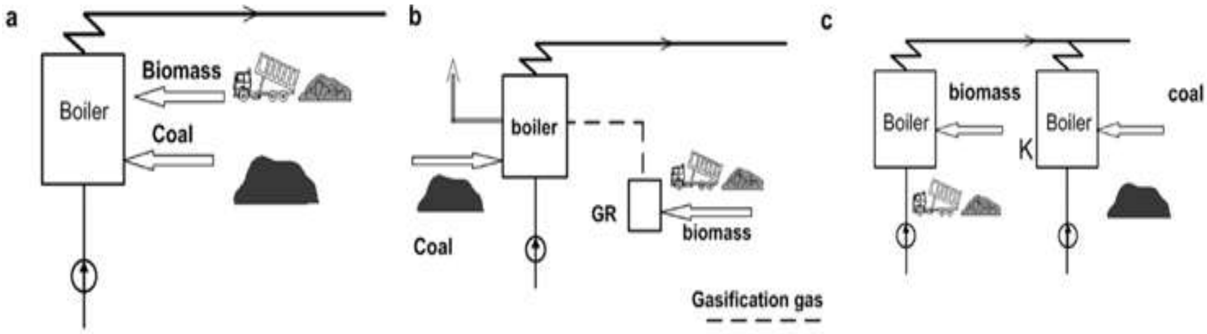


Figure 4.2. Biomass co-firing technologies: (a) direct co-firing; (b) indirect co-firing; (c) parallel co-firing (Al-Mansour, 2010)

Direct co-firing is the most commonly applied scheme. In this case, biomass fuel is combusted in the same furnace as a coal. The utilization of conventional coal handling and chopping equipment is also possible. As a result, this method is rather cheap.

There are three main classes of direct co-firing (Sami et al., 2001):

- Separate feed lines and separate burners for coal and biomass fuels
- Separate feed lines and a common burner
- Common feed lines and a common burner with premixed coal biomass blends

First class permits the better and independent control over fuel rates of coal and biomass. Simultaneously, separate equipment requires additional expenses. The second class is a relatively cheaper. At the same time, the quality of biomass fuel should be appropriate and high level of mixing is required. The third class is the most inexpensive among all represented possibilities due to the utilization of common facilities. It provides good mixing, high level of combustion and emissions reducing. Nevertheless, there is the risk of burner problems due to feeding difficulties and keeping up the given performance.

Another possibility of co-firing is installation of gasifier. Gasifier allows getting a fuel gas for combustion in coal furnace. This method is rather beneficial due to high caloric value of generated producer gas. In addition, proper gas cleaning before combustion will lead to minimization of harmful emissions and maximization of boiler performance.

Parallel co-firing unites two schemes: biomass combustion and coal combustion. Biomass boiler represents an additional source of steam in basic system. Although, this scheme requires rather high investments, it mitigates some possible fluctuation in biomass and coal supplying and permits stable generation.

Among other possible benefits, the reduction of harmful emissions is rather attractive. Since fossil fuel combustion is associated with emission of significant rates of air pollutants, in the co-firing methods emissions of oxides of sulphur SO_x and nitrogen NO_x are reduced. The reason of SO_x reduction is in the relatively low sulphur content of most kind of biomass materials. Woody biomass usually contains rather low nitrogen content in comparison with coal. Moreover, the addition of ammonia allows reducing NO_x emissions. Simultaneously, as soon as biomass is carbon-neutral material the decreasing of CO_2 emissions is achievable. The influence of CH_4 in greenhouse effect is stronger than for carbon dioxide. The landfilled biomass typically emits the methane. As a result, the utilization of various biomass residues helps to mitigate CH_4 emissions.

The high inorganic content of herbaceous biomass results some risks of fouling and slagging during combustion. At the same time, the utilization of fixed amount of biomass in co-firing application will not lead to some problems.

4.2 Boilers

In general, boiler represents closed container that provides heat transfer from hot source into the working media (usually water) until it reaches demanded condition. Boiler may produce hot water or steam that subsequently will be utilized in various processes, such us power generation, heating, etc.

From technical point of view the concept of steam boiler implies the whole complicated system for steam generation for usage, for instance, in a steam turbine or in numerous industrial processes. Primary energy of the fuel is released in the furnace part of the boiler. Boiler should be constructed in order to maximize heat absorption and transmission. This system includes the whole structure of equipment needed for heat transfer from burning fuel to working fluid: economizer, evaporating surfaces, superheater, and air preheater. Additionally, succeeding boiler performance demands varied auxiliary equipment systems, such as water treatment, fuel feeding, flue gas processing. (Teir, 2003)

Boilers can be divided into two groups: steam boilers and hot water boilers.

Steam boilers vary significantly and may be classified by various factors, such as type of circulation, combustion method, type of fuel, and other.

The main types of steam/water circulation are:

- Natural circulation: driving force in this case is the density difference between medium in downcomers and riser tubes
- Forced circulation: pump assists the movement of steam/water internal circulation
- Once-through principle: in this case water is moved once through all sequential stages of heat transfer surfaces

According to the utilized fuel, boilers can be divided into the following groups:

- Coal-fired
- Oil-fired
- Gas-fired
- Biomass-fired
- Multifuel-fired
- Heat recovery steam generators
- Refuse-fired

The main types of boilers in accordance with combustion method (Teir, 2003):

- Grate furnace boilers

- Cyclone firing
- Pulverized coal fired (PCF) boilers
- Oil- and gas-fired boilers
- Fluidized bed boilers

4.3 Fluidized bed (FB) boilers

Fluidized bed combustion is one of the most effective and reliable technologies for fuel utilization. In spite of rather long history of utilization in various industrial applications, only in the 1970s this technology was firstly applied to the large-scale utility (DeFusco et al., 2010).

The principle of combustion is based on burning fuel in layer of air-suspended mass of particles located at the bottom part of furnace. It consists of silica sand or other inert material. The fuel is introduced into this layer and combustion air is supplied from the furnace bottom through the sand layer. In dependence on the velocity of the applied stream of air, the layer gets different types of fluid-like behaviour that illustrated in Figure 4.3. (Teir, 2003)

In a case of secondary air application, it injected at the top of the bed (splashing zone) and further higher up (freeboard, also called as tertiary air) through well distributed air inlets over the entire walls of the boiler. (Khan et al., 2009)

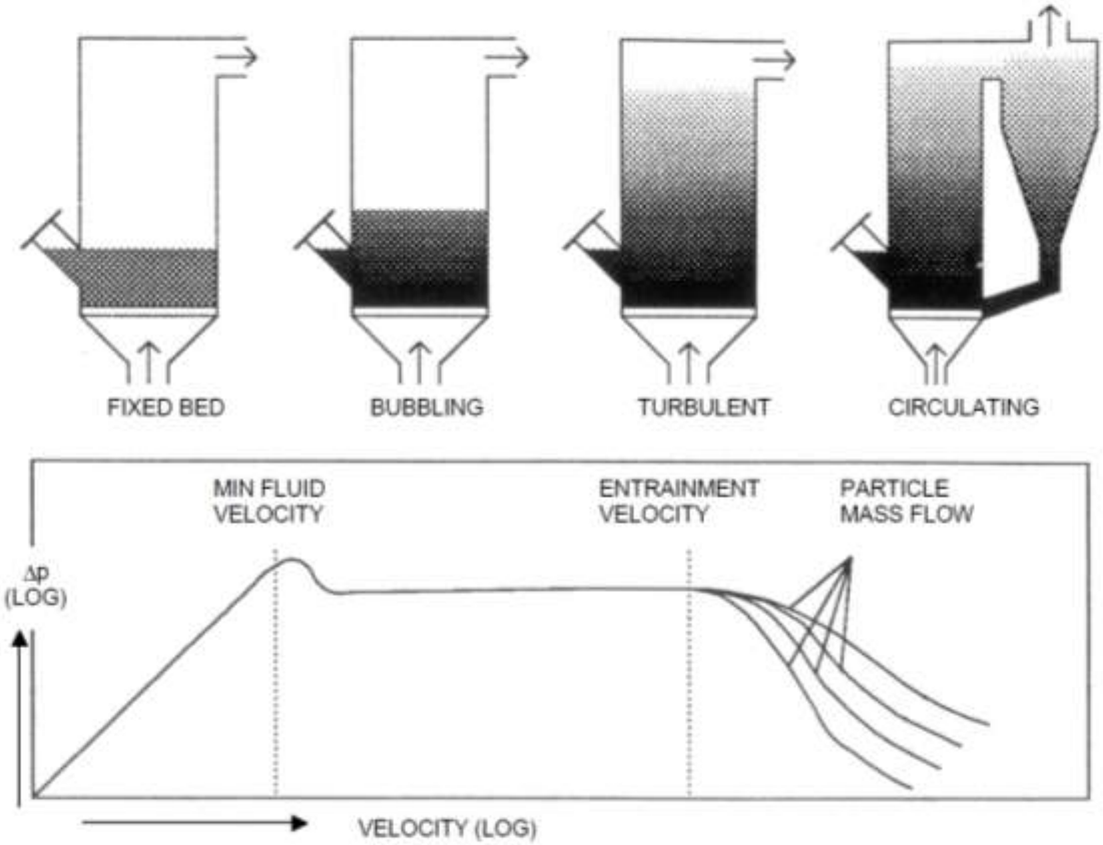


Figure 4.3. Regimes of fluidized bed boilers (Teir, 2003)

This type of combustion is rather attractive due to various benefits:

- High combustion and overall efficiency
- Fuel flexibility: FB boilers may be successfully operated with different types of fuels, even with low grade fuels
- High reliability due to the absence of moving parts in combustion zone
- Pollution control: SO_2 emissions can be considerably minimized by introducing of limestone into the bed material; NO_x formation is on the low level due to low combustion temperature
- Wide scope of feasible particle fuel sizes
- Simple operation and quick start-up

There are two main types of fluidized bed boilers: bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) boilers. Figure 4.4 illustrates the schematic views for CFB and BFB types of boilers. (Khan et al., 2009)

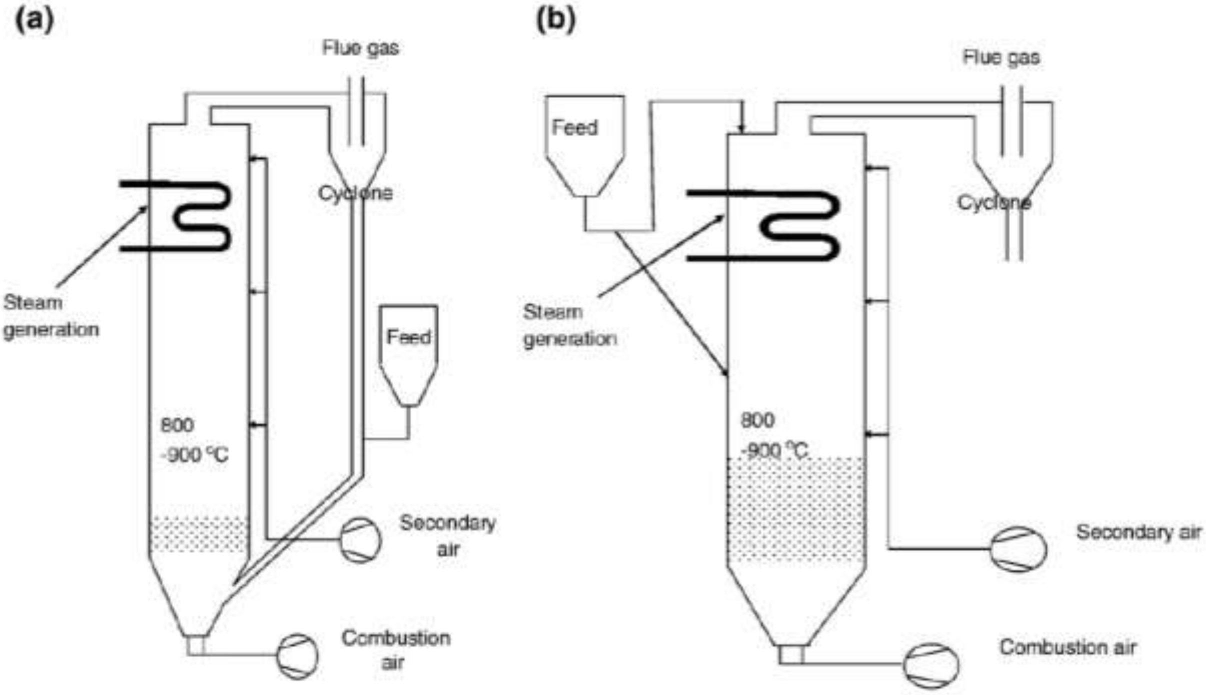


Figure 4.4. Schemes of circulating fluidized bed (a) and bubbling fluidized bed (b) boiler (Khan et al., 2009)

4.4 Circulating fluidized bed boilers

Circulating fluidized bed boilers operates under special dynamic conditions that provided transportation and mixing of fine solid particles through the furnace volume. Gas velocity is supported on the level around 3.0 - 6.0 m/s. Significant amount of solid particles are carried out from the bed layer due to high gas velocity. Major share of particles that abandon the furnace are captured by separator and recycled to the bottom part of the furnace. As a result, high rate of fuel combustion and mixing is achieved. (Teir, 2003)

Schematic view of CFB boiler is represented in Figure 4.5.

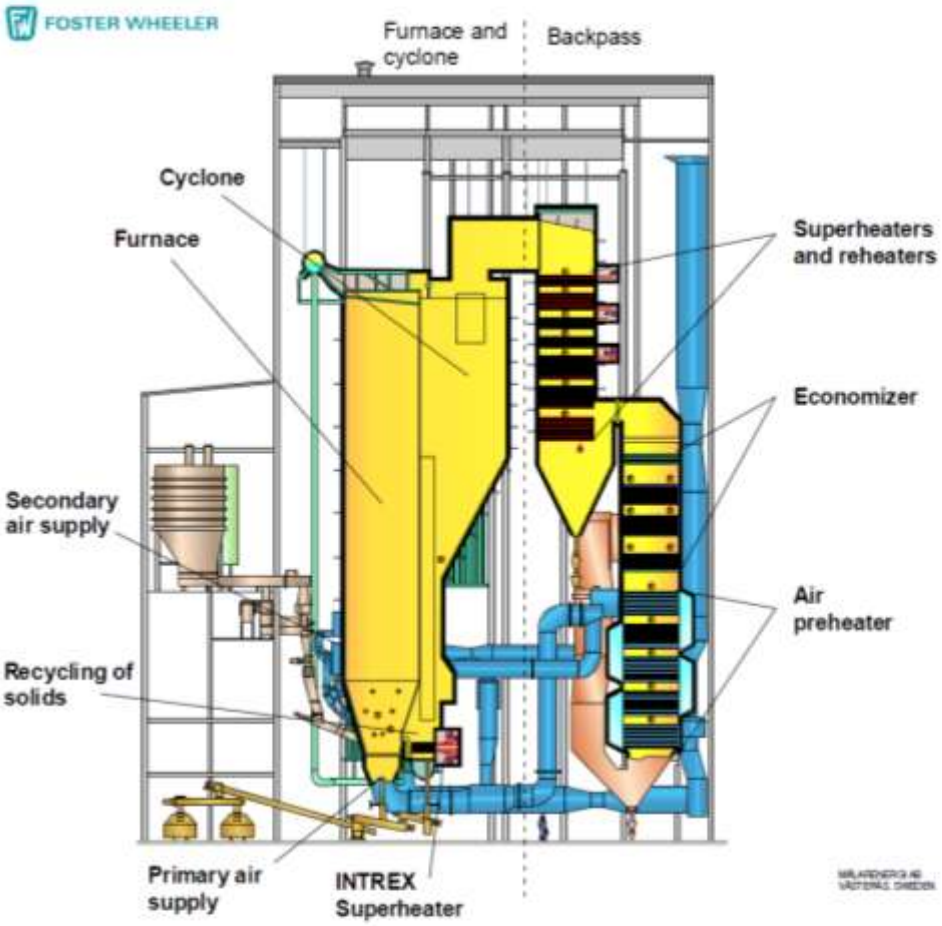


Figure 4.5. Schematic view of CFB boiler (Foster Wheeler, 2010)

Circulating fluidized bed boiler can be divided into two sections. First section includes the furnace, gas-solid separator, recycle device, and possible external heat exchangers. Another section, that typically named back-pass, consists of heat exchangers for absorption flue gasses heat, such as reheater, superheater, economizer, and air preheater. (Teir, 2003)

After fuel feeding into the sand layer at the bottom part of furnace, it fluidized by stream of primary air. Secondary air is injected above the layer in order to achieve effective combustion. Because of high fluidization velocities, high mixing rate for fuel is obtained, and uniform furnace temperature is fixed in the range of 800 – 900°C. Heavy solid particles that leave the bed layer are returned to it due to gravitation force. While other fractions are captured by gas-solid separator, also called as cyclone, and returned to the furnace. Final stage of gas and solid separation is implemented in bag-house filters or electrostatic precipitators. (Teir, 2003)

4.4.1 Combustion zones of CFB boilers

It is possible to assign three variant combustion zones in furnace of CFB boiler from the combustion standpoint: lower zone that is situated below the secondary air intake points; upper zone that is located above the secondary air intake points; and cyclone. The scheme of furnace combustion zones is illustrated in Figure 4.6. (Teir, 2003)

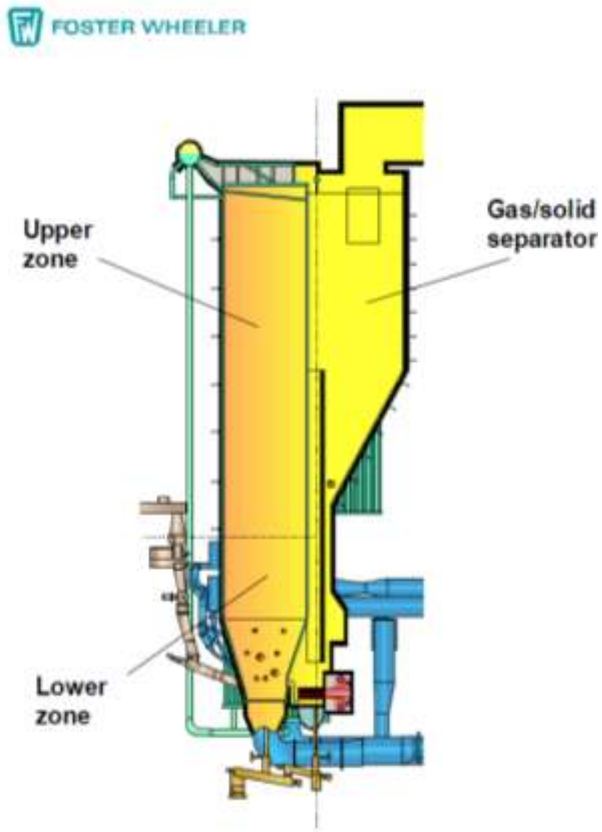


Figure 4.6. Schematic view of combustion zones of CFB boiler furnace (Foster Wheeler, 2010)

In the lower zone combustion is determined by primary combustion air flow. Additionally, solid particles, which are caught by cyclone, are conveyed to this part of furnace. In order to prevent corrosion and erosion tube damage, walls are covered with insulation. At the bottom of the furnace the particle density level is the highest, and it decreases with the furnace height. Due to high fluidization it is impossible to allocate the bed layer margins.

Secondary air supply ports form the upper combustion furnace zone. It results high oxygen concentration, and intensive combustion rate. Char fractions are transferred upwards, and then slide down the wall. Combustion of the char is completed during such repeated movements. Part of char that is occurred in gas-solid cyclone is separated from flue gases and is returned to the furnace for complete combustion. The efficiency of gas-solid separator characterizes the overall combustion efficiency. (Teir, 2003)

4.4.2 Heat exchanger surfaces of CFB boilers

Boiler includes consistent heat exchangers for effective transferring energy of burning fuel to the energy of heated media. Heat exchanger surfaces should be designed and arranged in such manner that the overall efficiency is supported on the high rate.

Heating surfaces for CFB boiler are the following:

- Evaporator
- Superheater
- Reheater (possible option)
- Economizer
- Air preheater

Typical arrangement of listed surfaces is shown in Figure 4.4.

Economizer is recuperative heat exchanger for transmitting heat from flue gasses to water. It is located at the back-pass section of the boiler. Flue gasses velocity is around 7.6 - 10.7 m/s and depends on the fuel type and ash characteristics. In order to avoid evaporation at the partial loads, outlet water temperature is limited in the limits of 42 °C less then saturation point. (Teir, 2003)

After economizer heated water is heated in the evaporation stage. It is represented by tube walls in the furnace where water absorbs heat from fuel combustion and turns into steam-water mixture.

Superheating is the next level of heat transfer. This heat exchanger is located in back-pass section, and there saturated steam is heated to the given steam parameters for subsequent expansion in turbine. Flue gasses velocity is around 7.6 - 8.5 m/s, while the steam velocity in tubes is about 20 m/s (Teir, 2003).

Reheating stage may be implemented in order to increase steam parameters after expansion in high pressure part of turbine. The reheater is located in back-pass section.

In air preheater combustion air is heated by flue gasses heat. This stage of heat transfer is usually located after economizer. Tube arrangement should minimize risk of erosion and fouling. Flue gasses are moved outside the tubes with velocity around 9 – 12 m/s (Teir, 2003).

An additional heat exchanger surface that was proposed by Foster Wheeler is the Integral Recycling Heat Exchanger (INTREX). The scheme of furnace with installed INTREX superheater is presented in Figure 4.7.

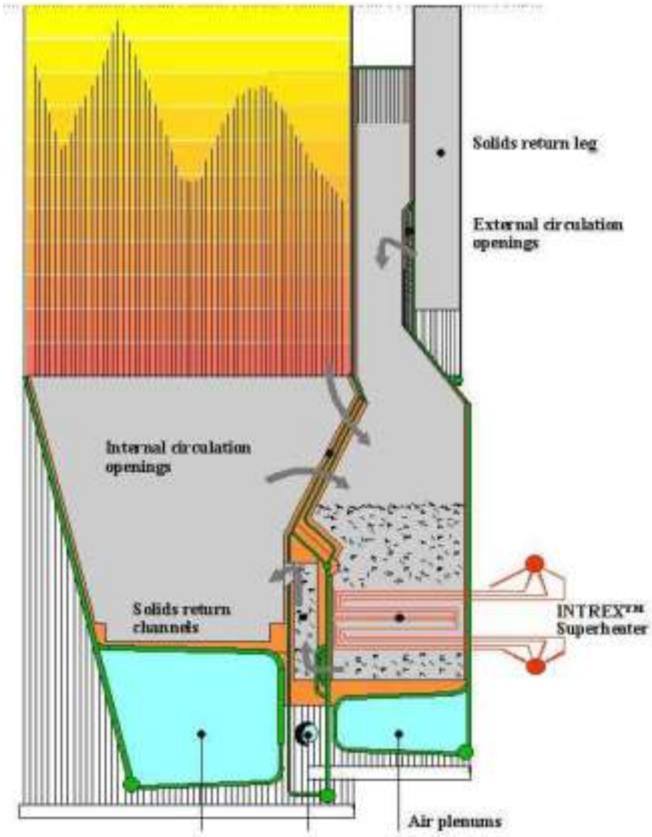


Figure 4.7. CFB boiler furnace with INTREX (Barišić et al., 2008)

Installation of INTREX allows extracting heat from the hot particles that are captured by cyclone (external circulation) and, in addition, from solids that are derived from the bottom part of furnace (internal circulation). It is represented by one or more tube bundles located in the bubbling bed. This kind of heat exchanger may be projected as additional superheater or reheater. Stable movement of solid matter prevents formation of deposits and ensures high heat transfer rate. The level of heat transfer can be controlled by the rate of air flow that applied for returning solids to the lower furnace. (Barišić et al., 2008)

4.4.3 Heat transfer processes

Heat transfer processes occurred during combustion in CFB boilers reasonably differ from those in conventional boilers. Clear understanding of these processes has significant importance for controlling combustion and achieving high efficiency. The schematic view of heat transfer processes in the furnace of CFB boiler is presented in Figure 4.8.

Several different heat transfer processes may be allocated: particle-gas heat transfer, heat transfer between different points in the bed, heat transfer between the fluidized bed particles and the larger particles floating in the bed, and the heat transfer to the submerged surfaces in contact with the bed (Rusheljuk, 2006).

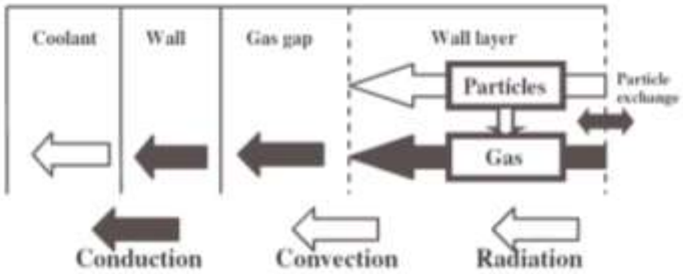


Figure 4.8. Scheme of heat transfer processes in the furnace of CFB boiler (Rusheljuk, 2006)

Numerous approaches proved that intensity and characteristics of these processes depend on various factors, such as suspension density, bed temperature, particle size, and length of heat transfer surface. Suspension density is the most important coefficient influenced on the heat transfer to the tube walls in the furnace. Bed temperature affects on the heat transfer coefficient: it increases because of higher thermal conductivity of gas and increased radiation at high temperatures. Particle size has an influence on the suspension absorption in a case of radiation heat transfer. (Basu, 1996) Although the level of fluidization has not great influence on the heat transfer processes, coefficient of heat transfer reduces with the height of the bed due to the temperature difference between cluster and tube wall. In the case of relatively short heat exchanging surfaces, fine solids result in high heat transfer coefficients but the influence is less significant for longer surfaces (Teir, 2003).

In the furnace of CFB boiler the following type of particle motion is observed. Small solids move upward through the core of the bed, then some part of them sinks downward along the wall forming the clusters, and the rest part moves up and down in dispersed phase (Teir, 2003). Suspension density decreases with the height.

Clusters transmit the heat to tubes through conduction and radiation processes, while dispersed particles transfer it through convection and radiation.

Conduction may be characterized as the energy transfer from particles with higher energetic content to particles with lower energy due to interactions between particles. The conduction takes place at the molecular level. Thermal conductivity of the material is determined by the material type.

Heat power provided by conduction - Fourier's Law (Teir, 2003):

$$\Phi_{\mathrm{cd}} = \lambda A \frac{T_1 - T_2}{s} \tag{4.1}$$

where Φ_{cd} is the heat power $[W]$

λ is the thermal conductivity of material $\left[\frac{W}{m \cdot K}\right]$

A is the heat transfer area $[m^2]$

$(T_1 - T_2)$ is the temperature difference $[K]$

s is the thickness of separating surface $[m]$

Figure 4.9 illustrates heat transmitting through a plane wall. Plane wall separates two media with different temperature levels. Heat transfer processes are the following: by convection heat flow from the hot media with the temperature $T_{\infty,1}$ to one wall surface that has temperature $T_{s,1}$, by conduction through the wall with length L, and finally by convection from other surface of wall with the temperature $T_{s,2}$ to the second media with temperature $T_{\infty,2}$. (Incropera et al., 2006)

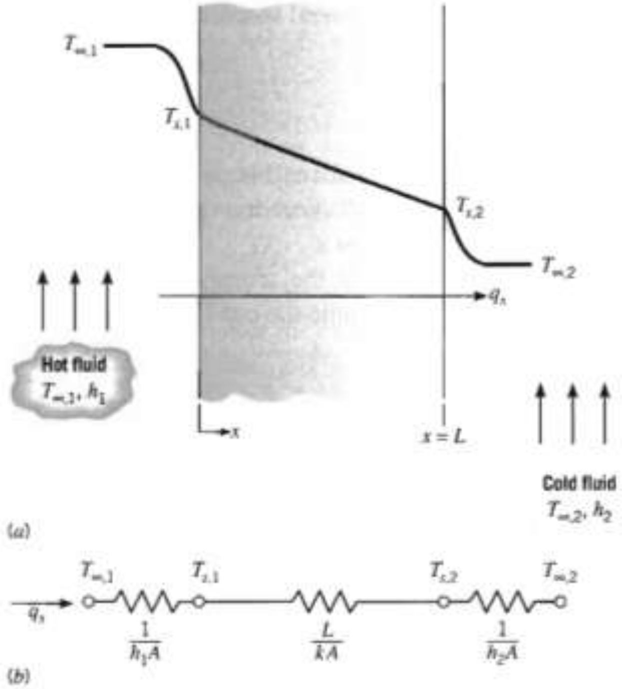


Figure 4.9. Heat transfer through a plane wall. Temperature distribution (a) and equivalent thermal circuit (b) (Incropera et al. 2006)

Convection represents the process of energy transfer between surface and fluid that moves over it. In a case of fluid motion due to density difference, convection is called a free convection. Otherwise, it is called forced convection. Heat transfer coefficient is depended on various parameters, as for instance flow velocity and pressure value.

Heat power provided by convection (Teir, 2003):

$$\Phi_{cv} = \alpha_c A(T_1 - T_2) \tag{4.2}$$

where Φ_{cv} is the heat power $[W]$

α_c is the heat transfer coefficient of media $\left[\frac{W}{m^2 \cdot K}\right]$

A is the area of heat transfer surface $[m^2]$

$(T_1 - T_2)$ is the temperature difference between surface and fluid $[K]$

Thermal radiation is an energy emitted by matter that is at a nonzero temperature (Incropera et al., 2006). Radiation can be emitted from heated materials - solids, liquids and gasses. In contrast with convection and conduction, radiation does not require the presence of material medium for heat transfer realization. The role of radiation increases with the temperature level growth. Thermal radiation is the main way for energy transfer in radiation heat transfer surfaces – furnace, radiation superheaters.

Heat power provided by radiation (Teir, 2003):

$$\Phi_r = \varepsilon_{fw} \sigma A \cdot (T_f^4 - T_w^4) \tag{4.3}$$

where Φ_r is the heat power $[W]$

ε_{fw} is the view factor between flame and water walls $[-]$

σ is the Stefan-Boltzmann constant $\left[\frac{W}{m^2 \cdot K^4}\right]$

A is the effective water wall surface $[m^2]$

T_f is the average gas temperature in the furnace$[K]$

T_w is the average water wall surface temperature $[K]$

The Stefan-Boltzmann constant $\sigma = 5{,}6787 \cdot 10^{-8} \left[\frac{W}{m^2 \cdot K^4}\right]$.

The value of ε_{fw} can be determined with following formula:

$$\varepsilon_{fw} = \left(\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} + 1\right)^{-1} \tag{4.4}$$

where ε_f is the emissivity of the flame $[-]$

ε_w is the emissivity of the wall $[-]$

Comprehensive analysis of heat transfer processes is rather complex. It is determined by radiation, particle convection, gas conduction and gas convection. In fact, the exact description of each contributor is problematic. At the same time, some simplifications may be applied. Typical example is the cluster renewal model that was introduced by (Subbarao, 1986). Since the wall is either covered by clusters or bared to gas, the time averaged total heat transfer coefficient can be defined as (Basu, 1996):

$$h_{total} = f h_p + (1 - f) h_g + h_r \tag{4.5}$$

where $\mathrm{h_{total}}$ is the time averaged total heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

h_p is the heat transfer coefficient due to particle convection $\left[\frac{W}{m^2 \cdot K}\right]$

h_g is the heat transfer coefficient due to gas convection $\left[\frac{W}{m^2 \cdot K}\right]$

h_r is the heat transfer coefficient due to thermal radiation $\left[\frac{W}{m^2 \cdot K}\right]$

f is the time averaged fractional area of the wall covered by solids $[m^2]$

Convective heat transfer on vertical tube walls may be characterized by using following equation from (Basu, 1996):

$$\mathrm{Nu} = 7.46 \cdot 10^{-4} \mathrm{Re_t^{0.757}}\, \mathrm{\rho_b^{0.562}} \tag{4.6}$$

where Nu is Nusselt number $[-]$

$\mathrm{Re_t}$ is Reynolds number based on bed diameter $[-]$

ρ_b is cross-section average bed density $\left[\frac{kg}{m^3}\right]$

The radiation heat transfer coefficient can be calculated (Basu, 1996):

$$\mathrm{h_r} = \varepsilon_{\mathrm{eff}} \sigma \frac{\mathrm{T_{susp}^4 - T_w^4}}{\mathrm{T_{susp} - T_w}} \tag{4.7}$$

where $\mathrm{h_r}$ is the radiation heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

$\mathrm{T_{susp}}$ is the suspension temperature $[\mathrm{K}]$

$\mathrm{T_{wall}}$ is the wall temperature $[\mathrm{K}]$

The value $\varepsilon_{\mathrm{eff}}$ can be determined with following formula:

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_b} + \frac{1}{\varepsilon_w} + 1\right)^{-1} \tag{4.8}$$

where ε_b is the equivalent emissivity of the bed $[-]$

ε_w is the emissivity of the wall $[-]$

Formula 4.5 may be improved (Dutta, 2004):

$$\mathrm{h_{total}} = \mathrm{f}\left(\mathrm{h_{c,cluster}} + \mathrm{h_{r,cluster}}\right) + (1 - \mathrm{f})\left(\mathrm{h_{c,dilute}} + \mathrm{h_{r,dilute}}\right) \qquad (4.9)$$

where $\mathrm{h_{c,cluster}}$ is the cluster convective heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

$\mathrm{h_{r,cluster}}$ is the cluster radiative heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

$\mathrm{h_{c,dilute}}$ is the dilute convective heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

$\mathrm{h_{r,dilute}}$ is the dilute radiative heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

As it was noted before, heat exchange rate in the furnace highly depends on suspension density. Typically the CFB furnace is divided into three zones: a dense bed, a splash zone, and an upper dilute zone. Dense bed has the highest density of solids, that then gradually decreasing due to back mixing processes (clustering and wall-layer flows). (Johansson et al., 2007) Figure 4.10 illustrates zones of CFB furnace.

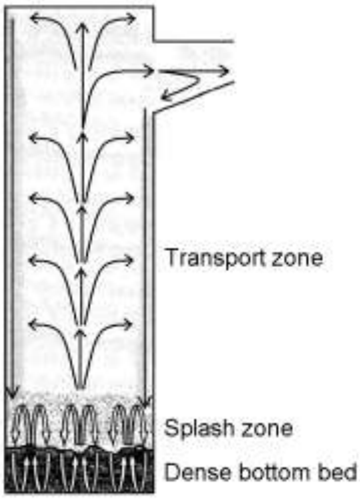


Figure 4.10. Zones of a CFB riser with corresponding mixing (Pallares, 2007)

Average suspension density of solids may be described as (Johansson et al., 2007):

$$\rho_s = \left(\rho_{s,Hx} - \rho_{2,Hx}\right) e^{-a(h-Hx)} + \rho_{s,exit} e^{K(H_{exit}-h)} \qquad (4.10)$$

where ρ_s is average suspension density of solids $\left[\frac{kg}{m^3}\right]$

$\rho_{s,Hx}$ is solids concentration at the top of bottom bed $\left[\frac{kg}{m^3}\right]$

$\rho_{2,Hx}$ is solids concentration due to dispersed phase at upper position of bottom bed $\left[\frac{kg}{m^3}\right]$

a is decay coefficient in splash zone $\left[\frac{1}{m}\right]$

Hx is the height of bottom bed $[m]$

$\rho_{s,exit}$ is solids concentration at gas exit $\left[\frac{kg}{m^3}\right]$

K is decay coefficient in transport zone $\left[\frac{1}{m}\right]$

$Hexit$ is the height (above air distributor) of centre of gas outlet $[m]$

h is the height above air distributor $[m]$

The value of $\rho_{2,Hx}$ can be found from:

$$\rho_{2,Hx} = \rho_{s,exit} e^{K(H_{exit} - Hx)} \tag{4.11}$$

Decay coefficient K may be found from (Johnsson, 1995):

$$K = \frac{0{,}23}{u_0 - u_t} \tag{4.12}$$

where u_0 is superficial gas velocity $\left[\frac{m}{s}\right]$

u_t is terminal gas velocity $\left[\frac{m}{s}\right]$

According to (Johansson et al., 2007), this equation can be simplified:

$$K = \frac{1}{H_t} \tag{4.13}$$

where H_t is the total height of furnace $[m]$

Decay coefficient a can be calculated (Johansson et al., 2007):

$$a = c\frac{u_t}{u_0} \tag{4.14}$$

where c is experimentally found coefficient $\left[\frac{1}{m}\right]$

Figure 4.11 illustrates solids concentration with dependence on height for various boilers. It can be noted that the density strongly decreases in the first zone of the furnace, and becomes rather stable since 5 – 10 m height. It can be explained by the influence of clustering flow in the splash zone, and solids back-mixing processes in the wall layers in transport zone.

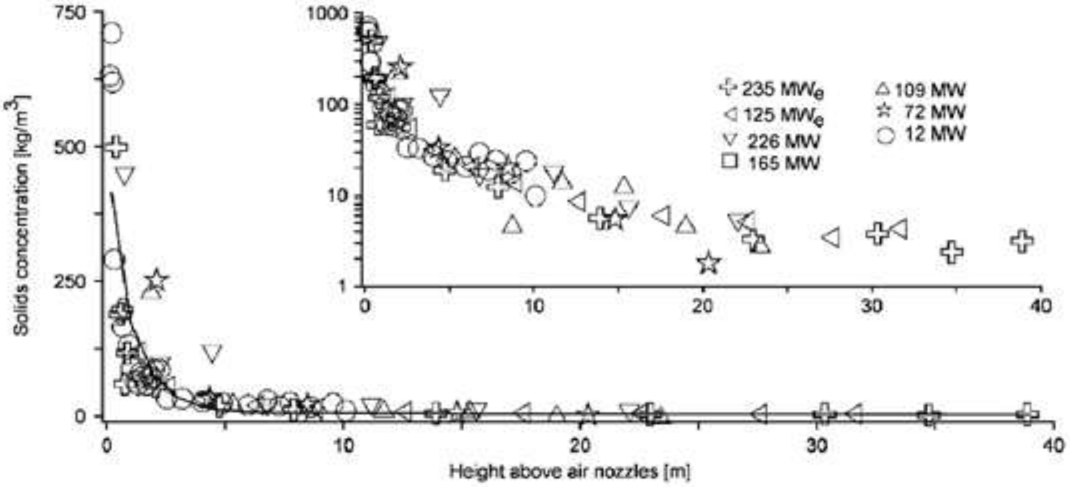


Figure 4.11. Solids concentration with dependence of height (Johansson et al., 2007)

4.5 Boiler deposits from biomass combustion

One of the most complex issues during biomass utilization in boilers is the ash depositions at the boiler heat transfer surfaces. Fouling of heat transfer surfaces means the deposits covering the surfaces. Slagging characterizes deposits on the furnace walls or other heat transfer surfaces exposed to predominantly radiant heat (Khan et al., 2009).

Slagging and fouling reduces rate of heat transfer and result other problems, as for instance corrosion and erosion of surfaces. As a result, overall performance and equipment reliability are affected.

The inorganic matter of the fuel is the main contributor to the deposits formation. Biomass fuels are characterized by a large variety of inorganic composition as compared to convenient fossil fuels. As a result, the deposit formation issues are rather crucial for biomass usage. The importance of this problem increases especially for some agricultural residues and new tree growth that are distinguish by relatively high alkaline content in ash (Sami et al., 2001). Alkali metals, sodium and potassium, represent major impact into deposition formation. In biomass materials these metals are presented in the form of organic compounds or as salts, and typically they are released during combustion (Nielsen et al., 2000). These chemical elements form alkali silicates that have low melting temperature (can be lower than 700°C), and, as result, ensure high risk of deposition formation. Basic scheme of potassium, sulphur, and chlorine chemistry in a biomass-fired boiler is presented in Figure 4.12.

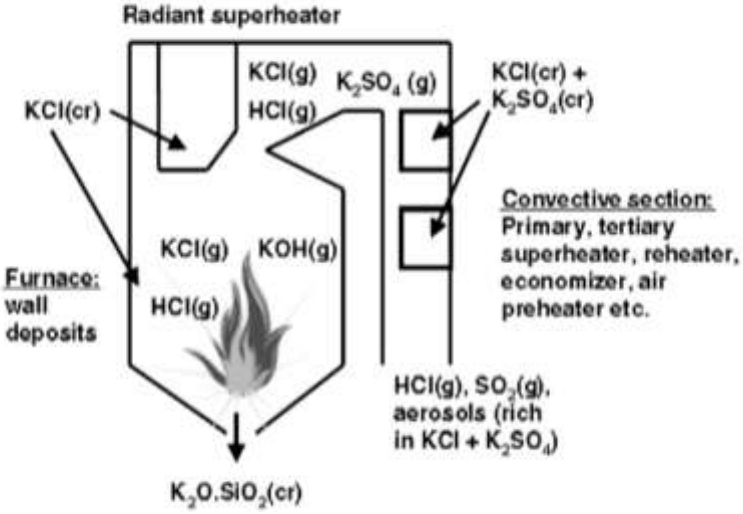


Figure 4.12. Principal pathways of potassium, sulphur and chlorine in biomass-fired boiler (Khan et al., 2009)

Chlorine has a significant importance in the process of alkali silicates formation. Chlorine content increases stability and volatility of alkali metals, releasing them as alkali chlorides and hydroxides in the gas phase. Typically chlorine concentration facilitates the transfer of alkali from the fuel to the surfaces. During cooling of the flue gasses in the convective area of boiler, alkali compounds nucleate and may condense on the heat transfer surfaces. In addition to this, some share of these chemicals may condense on fly ash which, in its turn, affects on heat exchangers surfaces. There is also possibility of reaction of alkali compounds with SO_2 that form sulfate compounds on the metal surfaces. (Khan et al., 2009) It was noted in various researches that chlorine content, rather than alkali, can be the limiting reactant in evaluation the total amount of alkali vapor produced (Miles et al., 1996).

The non-volatile compounds remaining in the charcoal consist such chemical elements as Ca, Mg and Si as well as of smaller level of bound volatile compounds such as K, Na and Al. In the case of fluidized bed combustion, significant part of ash forms the bottom ash in the furnace and cyclone ash. The rest of ash is conveyed with the flue gases and formed the coarse part of flyash. This matter may result depositions on various heat exchangers and lead to emissions. (Miles et al., 1996)

Surfaces oriented parallel to the gas flow and are responsive to small particles diffusion will possible collect a thin film of potassium sulfate. It was noticed in the spreader stokers firing wood with straw, wood with manure, and straw as a sole utilization. This process is unavoidable. Primary calculations of combustion processes should discount this effect. (Miles et al., 1996)

It was noted that most of woody biomass result scarce deposits problems in a case of burning alone. Simultaneously, co-firing with such materials, as straw and manure, cause deposits of K_2SO_4 and $CaSO_4$.

Typically, all metal surfaces of heat exchangers are attacked by various chemical elements or compounds. These processes result the releasing some alloy metals in different composition, thus making the metal structure more weaken. The most common corrosion mechanisms may be marked out in three classes (Nielsen et al., 2000):

- Corrosion associated with gas species (active oxidation)
- Solid phase corrosion
- Molten phase corrosion

The main remedy for mitigation of aforementioned effects is the capturing of alkali compounds. Some ways for implementation is an addition of different materials, such as bauxite, kaolinite, and limestone, in order to increase melting point of produced ash.

The alkali compounds may cause bed agglomeration problems. Agglomeration represents another important problem in the case of fluidized bed combustion, especially in the case of herbaceous biomass combustion. Without proper actions it may lead to breakdowns and unscheduled stops of the boiler. Silicon, calcium, potassium and aluminum are the agglomeration related components in biomass (Khan et al., 2009).

The main idea for mitigation of agglomeration risk is increasing the melting temperature of sintering compounds. There are several possibilities of it: co-combustion, pre-treatment, adding the special compounds, and utilization of alternative bed material. Co-firing permits delaying the time of agglomeration. Among most common additives are kaolin, dolomite, limestone, lime, and alumina (Khan et al., 2009). The changing of bed material is rather attractive way among others. It has rather easy implementation and low cost.

5 MODEL DEVELOPMENT

5.1 IPSEpro heat balance modeling software

IPSEpro program represents a set of software modules for creating process models and for utilizing these models throughout the lifecycle of process plants. This software is developed by SimTech Simulation Technology Company in Austria.

IPSEpro is a highly flexible environment for modeling, simulation, analysis and design of components and processes for energy and chemical engineering. (IPSEpro, 2003)

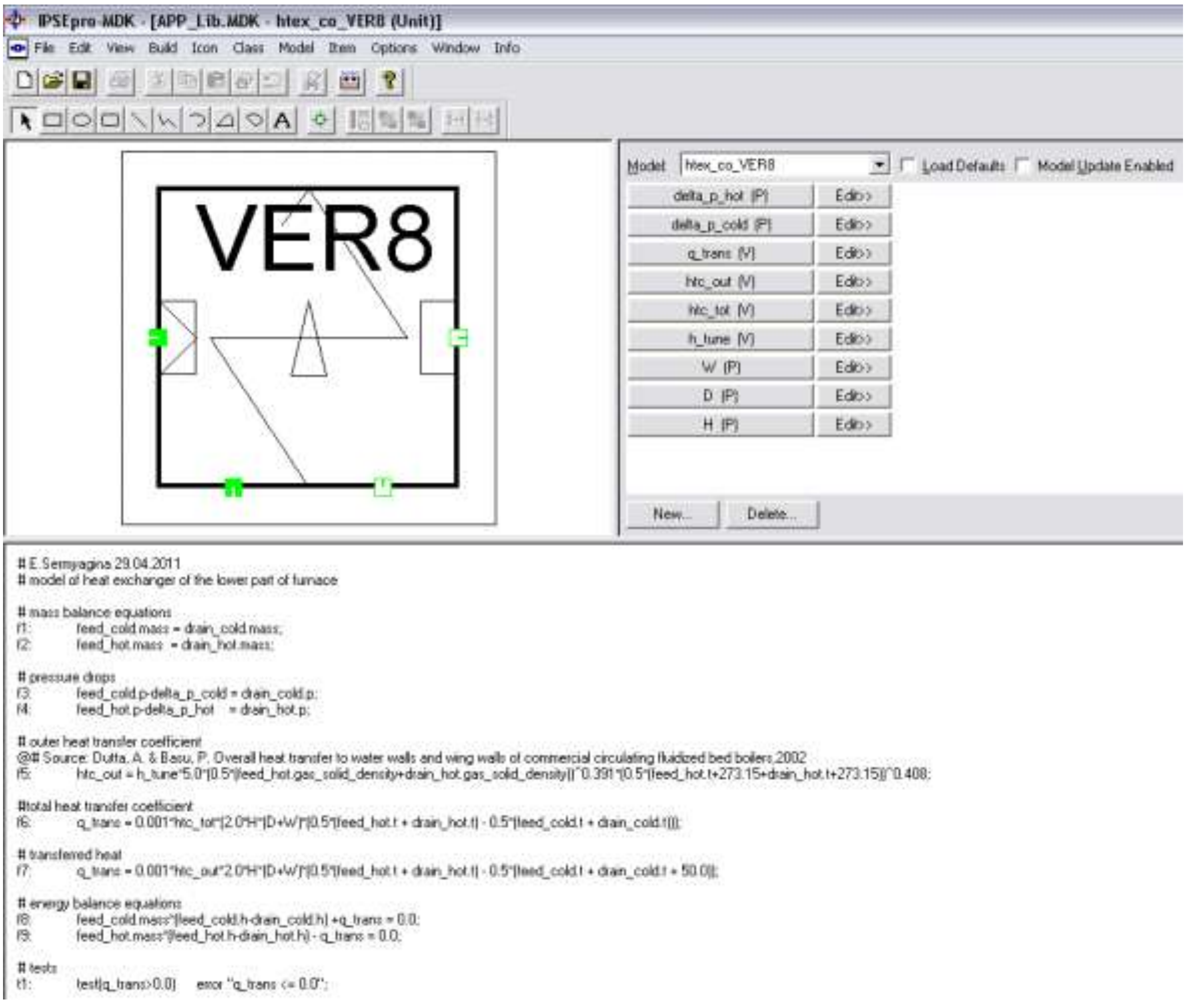
This software allows flexibility at two levels. First is the Component Level. IPSEpro allows constructing component models with various characteristics. This provides high flexibility of possible applications and accurate fulfillment of corresponding requirements. Model development process is quite interactive and easy. With IPSEpro’s Model Development Kit (MDK) the user can create graphically and mathematically a new model or modify the existing one from standard model libraries. Second level is the Process level. IPSEpro provides full freedom in arranging the existing components in required order to develop a process scheme. A graphical interface of the program enables easy access to any object of the scheme. Moreover, the calculations and presentation of essential results are also displayed in the project simulation window. IPSEpro’s Process Simulation Environment (PSE) allows gathering component models from component libraries and linking the elements. PSE provides efficient mathematical methods that ensure fast and accurate calculations. (IPSEpro, 2003) It is possible to review the behaviour of a single component of some process, part of the process or the whole scheme.

Mathematically, each component represents a number of variables and equations. For efficient work number of variables should be equal to number of equations. Model development constitutes the combining of all equations and variables into the entire system which presents the process model. As a result, modeling is based on solving a number of nonlinear equations.

The group of input values can be selected during the model developing (for instance, net power output instead of steam mass flow rate). Setting the initial values of variables is a quite essential factor for the system convergence. IPSEpro software provides default initial values. But in many cases, especially for unconventional applications, these values should be introduced manually. After successful solving the system, values of variables can be used as initial for the new calculation.

Design calculations are based on a system compiled from energy equations and various formulas that describe heat transfer processes, fluid properties and other process equations. The results of design calculation are used as a basis for off-design calculations. Additional characteristics and correlations are introduced in order to determine variations of some parameters (heat transfer coefficients, mass flows, pressure losses) in operation outside design conditions.

Model Development Kit provides the possibility of mathematical and graphical changes for components. MDK allows building model library that will match given requirements. It utilizes a model description language (MDL) that provides mathematical characterization of the model. The icon editor, in its turn, allows further component development. (IPSEpro, 2003) The operating window for MDK is represented in Figure 5.1.

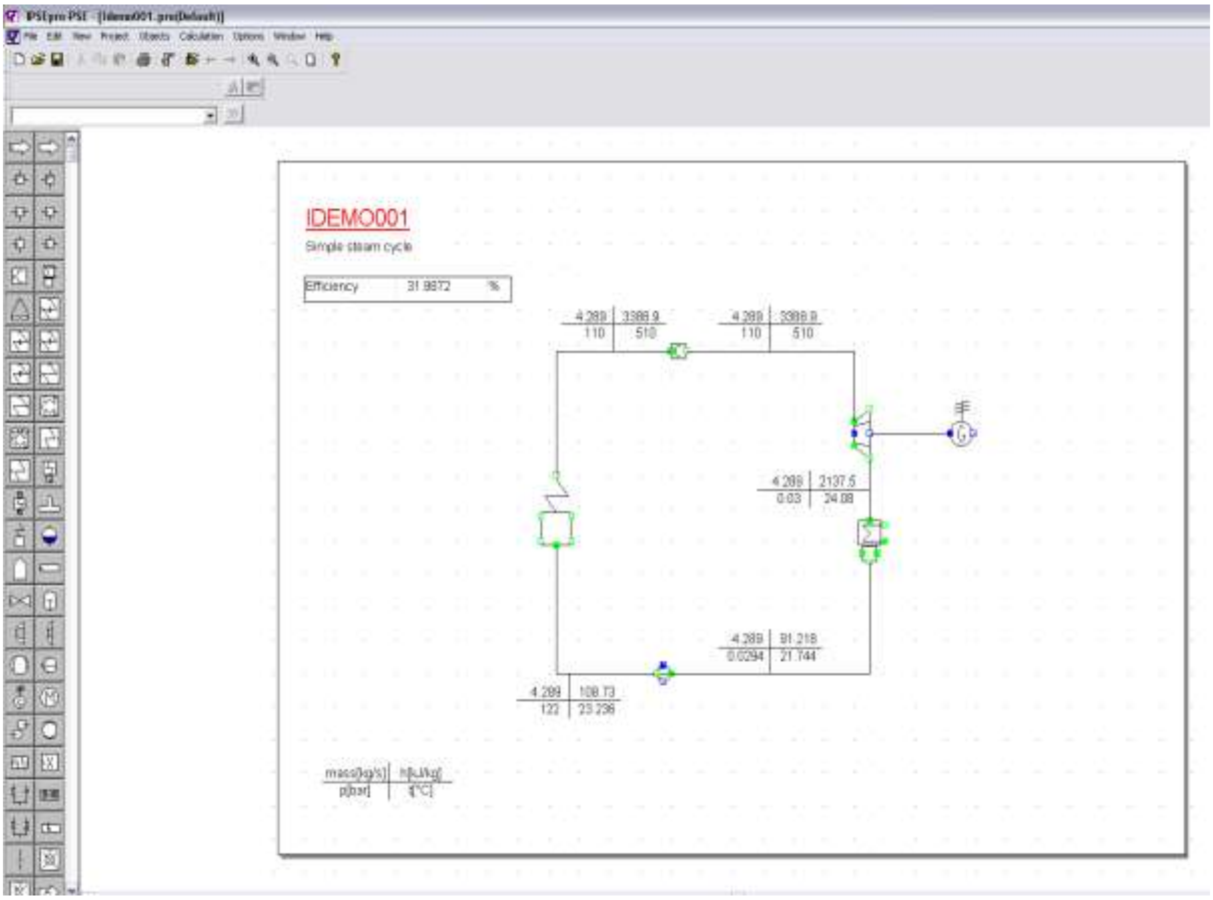


```
# E.Semyagina 29.04.2011
# model of heat exchanger of the lower part of furnace

# mass balance equations
f1:         feed_cold.mass = drain_cold.mass;
f2:         feed_hot.mass  = drain_hot.mass;

# pressure drops
f3:         feed_cold.p-delta_p_cold = drain_cold.p;
f4:         feed_hot.p-delta_p_hot    = drain_hot.p;

# outer heat transfer coefficient
@# Source: Dutta, A. & Basu, P. Overall heat transfer to water walls and wing walls of commercial circulating fluidized bed boilers,2002
f5:         htc_out = h_tune*5.0*(0.5*(feed_hot.gas_solid_density+drain_hot.gas_solid_density))^0.391*(0.5*(feed_hot.t+273.15+drain_hot.t+273.15))^0.408;

#total heat transfer coefficient
f6:         q_trans = 0.001*htc_tot*(2.0*H*(D+W))*(0.5*(feed_hot.t + drain_hot.t) - 0.5*(feed_cold.t + drain_cold.t));

# transfered heat
f7:         q_trans = 0.001*htc_out*2.0*H*(D+W)*(0.5*(feed_hot.t + drain_hot.t) - 0.5*(feed_cold.t + drain_cold.t + 50.0));

# energy balance equations
f8:         feed_cold.mass*(feed_cold.h-drain_cold.h) +q_trans = 0.0;
f9:         feed_hot.mass*(feed_hot.h-drain_hot.h) - q_trans = 0.0;

# tests
t1:         test(q_trans>0.0)    error "q_trans <= 0.0";
```

Figure 5.1. Operating window for Model Development Kit

Process Simulation Environment provides the creation of a process model from existing library components. One of positive features of PSE is that, for solving the system of equations, it collects them into groups, so the groups can be calculated one after one. The size of the group and, as a result, number of simultaneously solving equations is minimized. (IPSEpro, 2003)

The operating window for PSE is shown in Figure 5.2.



Efficiency 31.9872 %

Figure 5.2. Operating window for Process Simulation Environment

The Advanced Power Plant Library for IPSEpro has been created for modeling a wide amount of thermal systems.

The Advanced Power Plant Library permits to design and analyze any power plant, including:

- Combined-cycle plants
- Cogeneration plants
- Conventional plants

The library contains models for both design and off-design analysis. (IPSEpro, 2003)

PSExcel Integration is a module of the program that allows exchanging data between the PSE and MS-Excel. This unit of the program permits transferring data obtained from the PSE to the MS-Excel and allows further analyzing and utilization of the data in MS-Excel, or creating a report with data on the work done in PSE. Another advantage of the PSE-MS-Excel Integration Module is the possibility of transfer to Excel series of different calculations with model. These calculations can be obtained by varying some parameters of system components. (IPSEpro, 2003)

5.2 Boiler model basis

The boiler model is based on a concept of CFB boiler that operated in Foster Wheeler Advanced Bio CFB’s Kaukas power plant located UPM-Kymmene Paper Mill site in Lappeenranta, Finland. The considered plant produces electricity and process steam for the paper mill site and district heat for the city of Lappeenranta. The characteristics of overall boiler operation are used for model development, nevertheless, the detailed configuration and process values of the model do not represent the actual boiler accurately.(Jantti et al., 2010)

The boiler concept of CFB boiler of Kaukaan Voima Oy is shown in Figure 5.3.

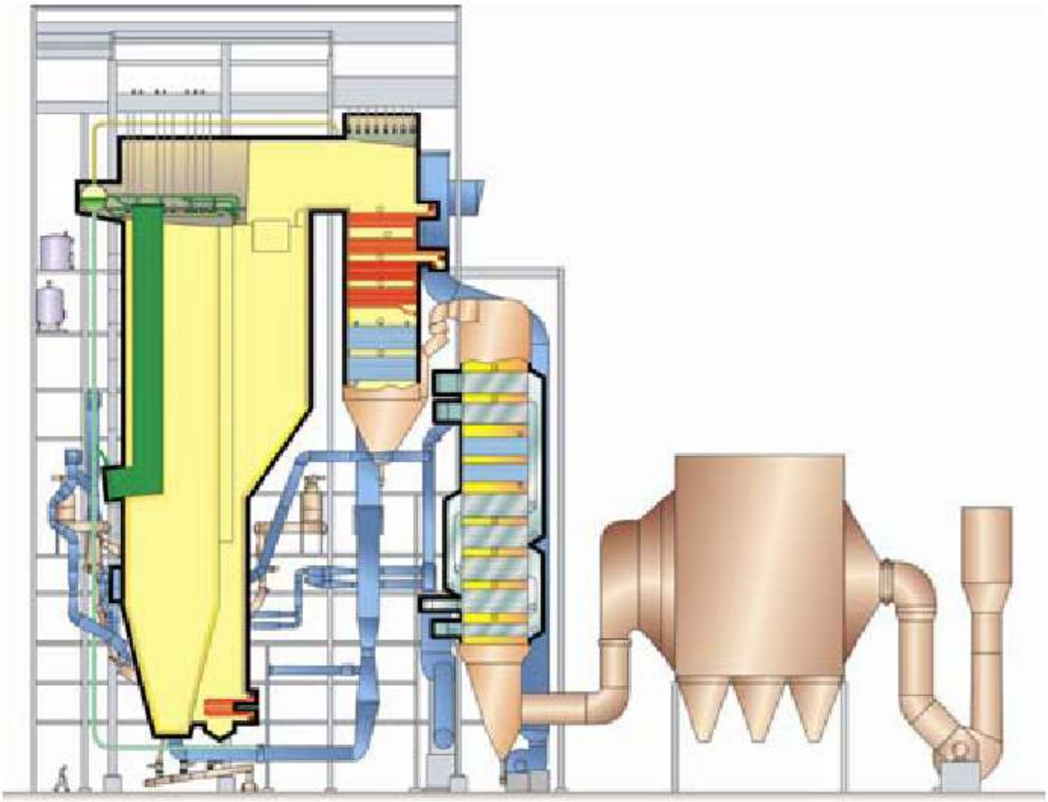


Figure 5.3. Boiler concept of Kaukas CFB (Jantti et al., 2010)

The steam data and design performance characteristics are presented in Table 5.1 (Jantti et al., 2010).

Table 5.1. Steam data and design performance characteristics for Kaukas CFB boiler

Total heat output [MWh]	385	
Steam flow [kg/s]	149	
Steam pressure [bar]	115	
Steam temperature [°C]	550	
Feedwater temperature [°C]	213	
Boiler efficiency [%]	91	
Flue gas exit temperature [°C]	Peat	Biomass
	140	149

The boiler can be fired on peat and woody residues - pulp and paper mill by-products, such as bark, sludge, and forest residues. Both types of fuel can be fired separately or co-fired. The fuel data are represented in Table 5.2. (Jantti et al., 2010)

Table 5.2. Kaukas CFB boiler fuel data

Fuel property	Fuel	
	Peat	Biomass
Moisture [Wt %]	45	48
Ash [dry Wt %]	5.0	2.5
Nitrogen [dry Wt %]	1.9	0.6
Sulphur [dry Wt %]	0.2	0.05
LHV $\left[\frac{MJ}{kg}\right]$	11.3	9.2

In order to maintain the required level of emissions, the boiler is equipped with an electrostatic precipitator (ESP) and ammonia injection both in the furnace and the separator, thus selective non-catalytic NO_x reduction (SNCR) technique can be applied. In addition, for desulphurization purposes limestone injection in the furnace is utilized. The boiler design is based on standard Foster Wheeler CFB design for clean biomass fuels. Characteristic features of such design are the following: the fully integrated water cooled solids separator (cyclone) and return leg, an INTREX^{TM} superheater, wing wall heat transfer surface, and applying the refractory material at the furnace bottom. (Jantti et al., 2010)

5.3 Boiler model development

Research results and various models on processes of heat transfer, combustion and mixing in circulating fluidized bed boilers have been broadly reported in wide number of reports. Nevertheless, there is a small amount of publicly available experiment data on these processes in large scale units, and results obtained in laboratory units cannot always been applied to boiler design. The developed model is a continuation of the model reported in (Ovsyannikov, 2010). In addition, plenty of useful information for modeling heat transfer in the boiler furnace was found in (Viljanen, 2010).

The nature of heat transfer in the furnace of a CFB boiler is rather complex. The heat transfer characteristics are determined by different factors. As a result, proposed models often constitute quite complicated systems. Such models may have rather high reliability but not high level of practical applications due to wide range of necessary variables. At the same time, clear understanding of mechanisms can lead to simplified and easy applicable heat transfer models.

Fuel particles and bed material represent a solid matter suspension in the furnace of the CFB boiler. The character of solids distribution in the furnace has an essential influence on the heat transfer processes. CFB boilers are operated in a closed loop. It means that the major part of solids, leaving the furnace, is returned back. After return leg and INTREX heat exchanger, the solids are introduced into the furnace and are mixed with the gases. Solids and gas move through the furnace in co-current two-phase stream. Since the particles enter the furnace with low vertical velocity, they are accelerated by gas forces (Teir, 2003).

Particle distribution varies both in axial and radial directions of the bulk flow in the CFB furnace. Various models have been developed in order to describe the hydrodynamics in the CFB furnace. In the present work some assumptions were used for the simplification of the model. The properties of the gas-solid suspension are determined by both gas and solids characteristics. The separate volume of the furnace space is composed of the define amount of gas media and the define amount of solids. The mass fraction of solid material can be found from basic equations for material density. Consequently, in the model the mass fraction of solids in the gas-solid suspension is introduced:

$$y_s = \frac{m_s}{m} = \frac{m_s}{m_s + m_g} = \frac{1}{1 + \frac{\rho_g}{\rho_s} - \frac{\rho_g}{\rho_{sol}}} \tag{5.1}$$

where y_s is the mass fraction of solids in the gas-solid suspension [-]

m is mass of gas-solid suspension $[kg]$

m_s is mass of solid phase $[kg]$

m_g is mass of gas phase $[kg]$

ρ_s is gas-solid suspension density $\left[\frac{kg}{m^3}\right]$

ρ_{sol} is solid phase density $\left[\frac{kg}{m^3}\right]$

ρ_g is gas phase density $\left[\frac{kg}{m^3}\right]$

The introduced variable allows considering the properties for both solids and gas phases of gas-solid suspension in determining enthalpy values.

$$h_{susp} = (1 - y_s)h_g + y_s h_s \tag{5.2}$$

where h_{susp} is the enthalpy of gas-solid suspension $\left[\frac{kJ}{kgK}\right]$

h_g is the enthalpy of gas $\left[\frac{kJ}{kgK}\right]$

$\mathrm{h_s}$ is the enthalpy of solids $\left[\frac{\mathrm{kJ}}{\mathrm{kgK}}\right]$

As it was mentioned before, the main heat transfer processes between gas-solid suspension and walls are gas and solid convection, and thermal radiation. Although the total heat transfer is formed from all three modes, the share for each particular mode may vary. Progression of combustion and heat transfer processes in CFB riser depends on the suspension density and suspension temperature in the different parts of the furnace.

In the present work, the furnace volume was divided into ten segments in order to differentiate the character of heat transfer. Furnace is formed by sequence of heat exchangers. Figure 5.4 represents the schematic view of the boiler furnace model.

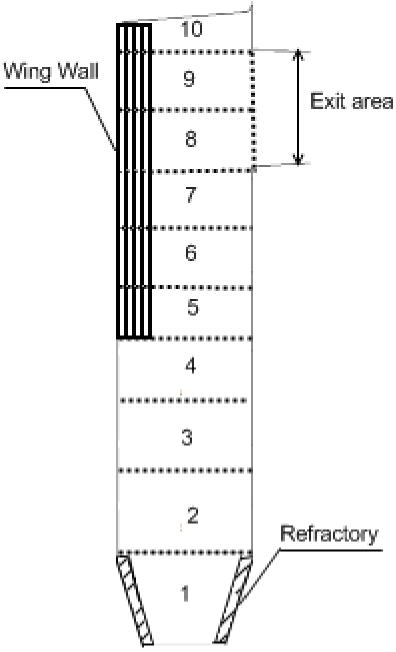


Figure 5.4. The schematic view of the furnace model

First segment corresponds to heat transfer at the bottom part of the furnace. In order to protect membrane wall from high temperature effects, wall surface is covered with refractory layer. Next three unites of the model represent membrane tube walls in the boiler furnace. Next four modules of the model are constituted as double heat exchangers. This allows considering both characters of heat transfer: for membrane wall and wing wall. Additionally, effect of exit zone is taken into account in calculation of transferred heat in next two segments. The last heat exchanger in the furnace is designed for heat transfer calculation in roof zone.

The heat transfer between gas-solid suspension and the walls may be calculated with empirical relation that was proposed by (Dutta, Basu 2002b):

$$h_{out} = 5\rho_s^{0.391} T_{susp}^{0.408} \tag{5.3}$$

where h_{out} is the outer heat transfer coefficient $\left[\frac{W}{m^2 K}\right]$

ρ_s is the average suspension density $\left[\frac{kg}{m^3}\right]$

T_{susp} is the average suspension temperature $[K]$

In order to receive an extra heat from the furnace of CFB boiler, additional heating surfaces may be installed. Wing walls are essential parts of CFB boiler furnace. This heat transfer surface may represent either a part of the evaporator or superheater. Typically, wing walls hang from the roof and extend from the front wall to some distance towards the opposite wall, where the furnace exit is located. (Dutta, 2002a) Heat transfer conditions for such heat transfer surface are differed from convenient water tube walls. The outer heat transfer coefficient to wing wall may be found with the following empirical correlation (Dutta, 2002b):

$$h_{out} = 3.6\rho_s^{0.37} T_{susp}^{0.425} \tag{5.4}$$

where ρ_s is the average suspension density $\left[\frac{kg}{m^3}\right]$

T_{susp} is the average suspension temperature $[K]$

Heat rate transferred in each segment of the furnace volume may be found as:

$$q_{trans} = \mathrm{h_{out}A}\left(\mathrm{T_{susp}} - \mathrm{T_{wall}}\right) \tag{5.5}$$

where $\mathrm{h_{out}}$ is the outer heat transfer coefficient $\left[\frac{W}{m^2 K}\right]$

$\mathrm{T_{susp}}$ is the average suspension temperature $[°\mathrm{C}]$

$\mathrm{T_{water}}$ is the average water temperature $[°\mathrm{C}]$

As a result of refractory cover at the bottom part of the furnace, the rate of heat transfer at the first segment decreases. The surface temperature of refractory layer is determined in accordance to Fourier's Law – equation (4.1):

$$\mathrm{T_{refr}} = T_{wall} + \frac{q_{trans} \cdot \Delta S_{ref}}{\lambda_{ref} \cdot A} \tag{5.6}$$

where λ_{ref} is the thermal conductivity of refractory material $\left[\frac{W}{m \cdot K}\right]$

A is the heat transfer area $[m^2]$

T_{refr} is the temperature of refractory $[°\mathrm{C}]$

T_{wall} is the temperature of water tubes surface $[°\mathrm{C}]$

ΔS_{ref} is the thickness of refractory layer $[m]$

The temperature of water tubes surface from the furnace side is assumed as 25 degrees more than water temperature inside the tubes (Dutta, 2002b).

In a case of bottom part of the furnace heat rate is calculated:

$$q_{trans} = \mathrm{h_{out}A(T_{susp} - T_{refr})} \tag{5.7}$$

where $\mathrm{h_{out}}$ is the outer heat transfer coefficient $\left[\frac{W}{m^2 K}\right]$

$\mathrm{T_{susp}}$ is the average suspension temperature $[°\mathrm{C}]$

$\mathrm{T_{water}}$ is the average water temperature $[°\mathrm{C}]$

In all cases total heat rate transferred in each segment of the furnace volume may be found as:

$$q_{trans} = \mathrm{U_{total}A(T_{susp} - T_{water})} \tag{5.8}$$

where $\mathrm{U_{total}}$ is total heat transfer coefficient $\left[\frac{W}{m^2 K}\right]$

$\mathrm{T_{susp}}$ is the average suspension temperature $[°\mathrm{C}]$

$\mathrm{T_{water}}$ is the average water temperature $[°\mathrm{C}]$

Energy balance equations that characterize heat transfer processes in the furnace are the following:

$$q_{trans} = \dot{m}_{hot}\left(h_{hot\ in} - h_{hot\ out}\right) \tag{5.9}$$

where q_{trans} is transferred heat $[kW]$

$\dot{m}_{hot}$ is mass flow of high temperature side $\left[\frac{kg}{s}\right]$

$h_{hot\ in}$ is inlet enthalpy of high temperature side $\left[\frac{kJ}{kg}\right]$

$h_{hot\ out}$ is outlet enthalpy of high temperature side $\left[\frac{kJ}{kg}\right]$

$$q_{trans} = m^{\cdot}_{cold}\left(h_{cold\ out} - h_{cold\ in}\right) \tag{5.10}$$

where $m^{\cdot}_{cold}$ is mass flow of low temperature side $\left[\frac{kg}{s}\right]$

$h_{cold\,in}$ is inlet enthalpy of low temperature side $\left[\frac{kJ}{kg}\right]$

$h_{cold_{out}}$ is outlet enthalpy of low temperature side $\left[\frac{kJ}{kg}\right]$

For determination of heat transfer rate in back pass heat exchangers, the logarithmic temperature difference is used:

$$\Delta T_{log} = \frac{\Delta T_{larger} - \Delta T_{smaller}}{ln\frac{\Delta T_{larger}}{\Delta T_{smaller}}} \tag{5.11}$$

where ΔT_{larger} is the larger temperature difference between two media $[K]$

$\Delta T_{smaller}$ is the smaller temperature difference between two media $[K]$

As a result, heat transfer rate in these heat exchangers can be found:

$$q_{trans} = \mathrm{htc}_{\mathrm{area}\Delta T_{log}} \tag{5.12}$$

where $\mathrm{htc\_area}$ is the dimensionless conductance $\left[\frac{kW}{K}\right]$

ΔT_{log} is the logarithmic temperature difference $[K]$

Introducing the dimensionless conductance allows avoiding the geometric values inputs in design and off-design conditions. For off-design simulations certain correlations were used for the heat transfer coefficients determination and geometric dimensions of heat transfer surfaces are taken as constants. The total heat transfer coefficient is assumed to remain its design value in the solids separator and return leg as well as INTREX walls and superheater.

For the heat exchangers in the back passage with the exhaust gas on the hot side , the variation of the total heat transfer coefficient is assumed to be dominated by the convection heat transfer between the exhaust gases and tube outer surface. Therefore, applying the correlation for the Nusselt number in case of flow across the tube banks with 10 or more rows the variation of total heat transfer coefficient can be approximated to depend only on exhaust gas mass flow (Kaikko, 2007).

$$\frac{h_{tot}}{h_{tot,0}} = \left(\frac{\dot{m}_{gas}}{\dot{m}_{gas,0}}\right)^{0.6} \tag{5.13}$$

where h_{tot} is the total heat transfer coefficient $\left[\frac{W}{m^2 K}\right]$

$h_{tot,0}$ is the total heat transfer coefficient in design case $\left[\frac{W}{m^2 K}\right]$

$\dot{m}_{gas}$ is the mass flow of the exhaust gases $\left[\frac{kg}{s}\right]$

$\dot{m}_{gas,0}$ is the mass flow of the exhaust gases in design case $\left[\frac{kg}{s}\right]$

It must be noted that the validity of assuming dominant hot side convection is decreased at higher temperatures due to radiation influence.

For off-design modeling, certain correlations for pressure losses are introduced. The variation of pressure losses on the water, gas-solid suspension and exhaust gas sides follows the standard IPSEpro assumption of dependency only on the mass flows (IPSEpro, 2003).

$$\frac{\Delta p}{\Delta po} = \left(\frac{\dot{m}}{\dot{m}o}\right)^{2} \tag{5.14}$$

where Δp is the pressure losses $[bar]$

Δpo is the pressure losses in design case $[bar]$

$\dot{m}$ is the mass flow of the media $\left[\frac{kg}{s}\right]$

$\dot{m}o$ is the mass flow of the media in design case $\left[\frac{kg}{s}\right]$

For the solids flow, pressure and pressure losses are not taken into account.

As a result, the entire system of presented equations permits the accurate calculation of heat transfer from gas-solid suspension to water tubes in the furnace.

The schematic view of the model in IPSEpro software is presented in Figure 5.6 and Figure 5.7. The following symbols and notations that were used are presented in Figure 5.5.

SH – Superheater

DSH – Desuperheater

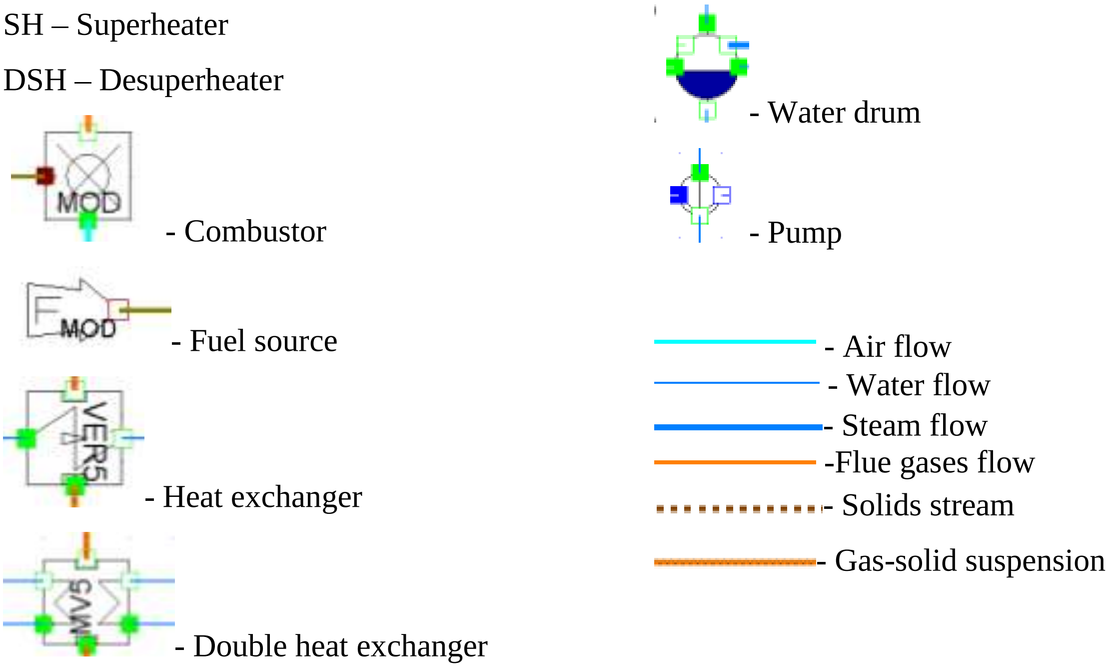


Figure 5.5. Symbols and notations

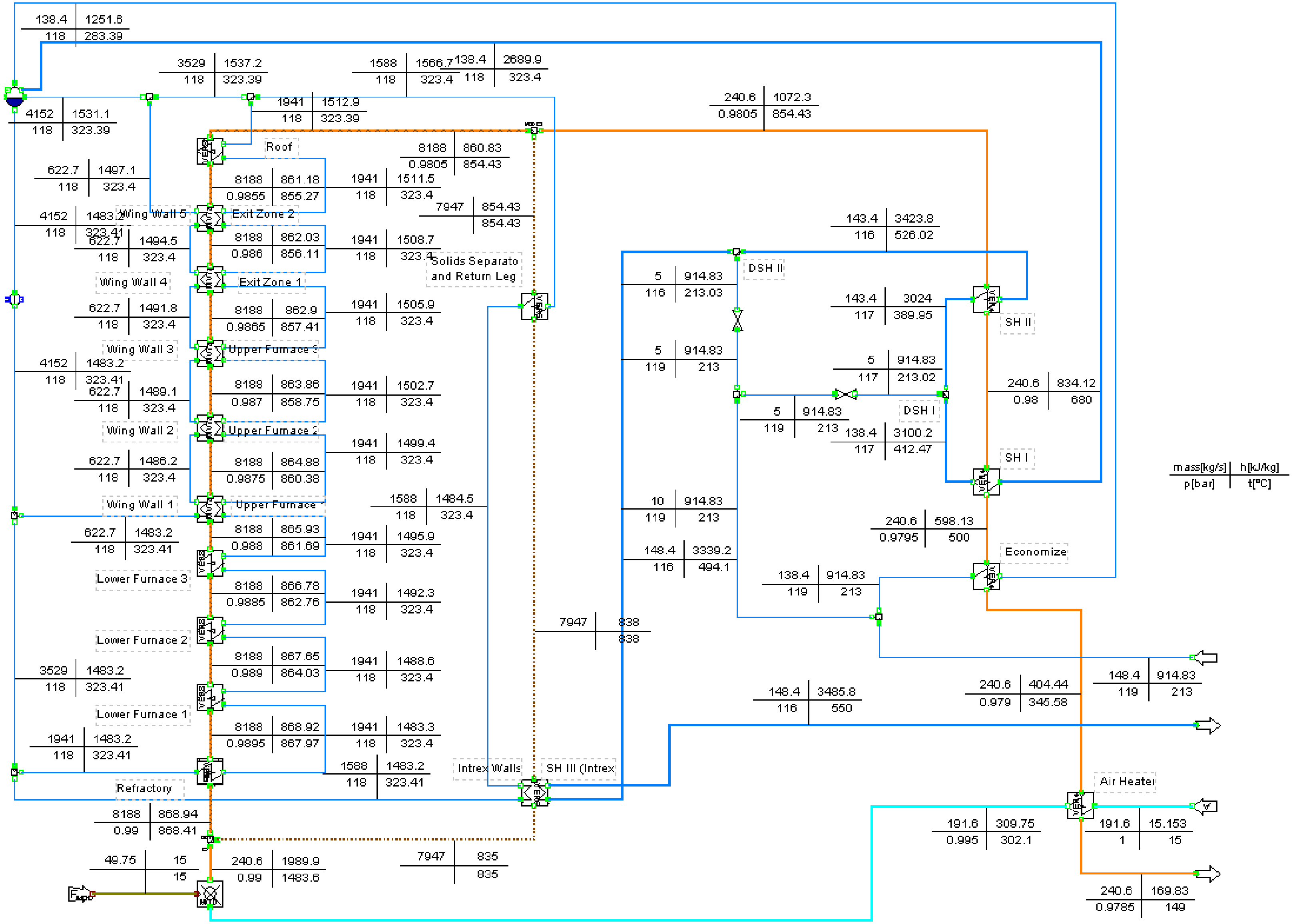


Figure 5.6. Boiler model with design-point operating values

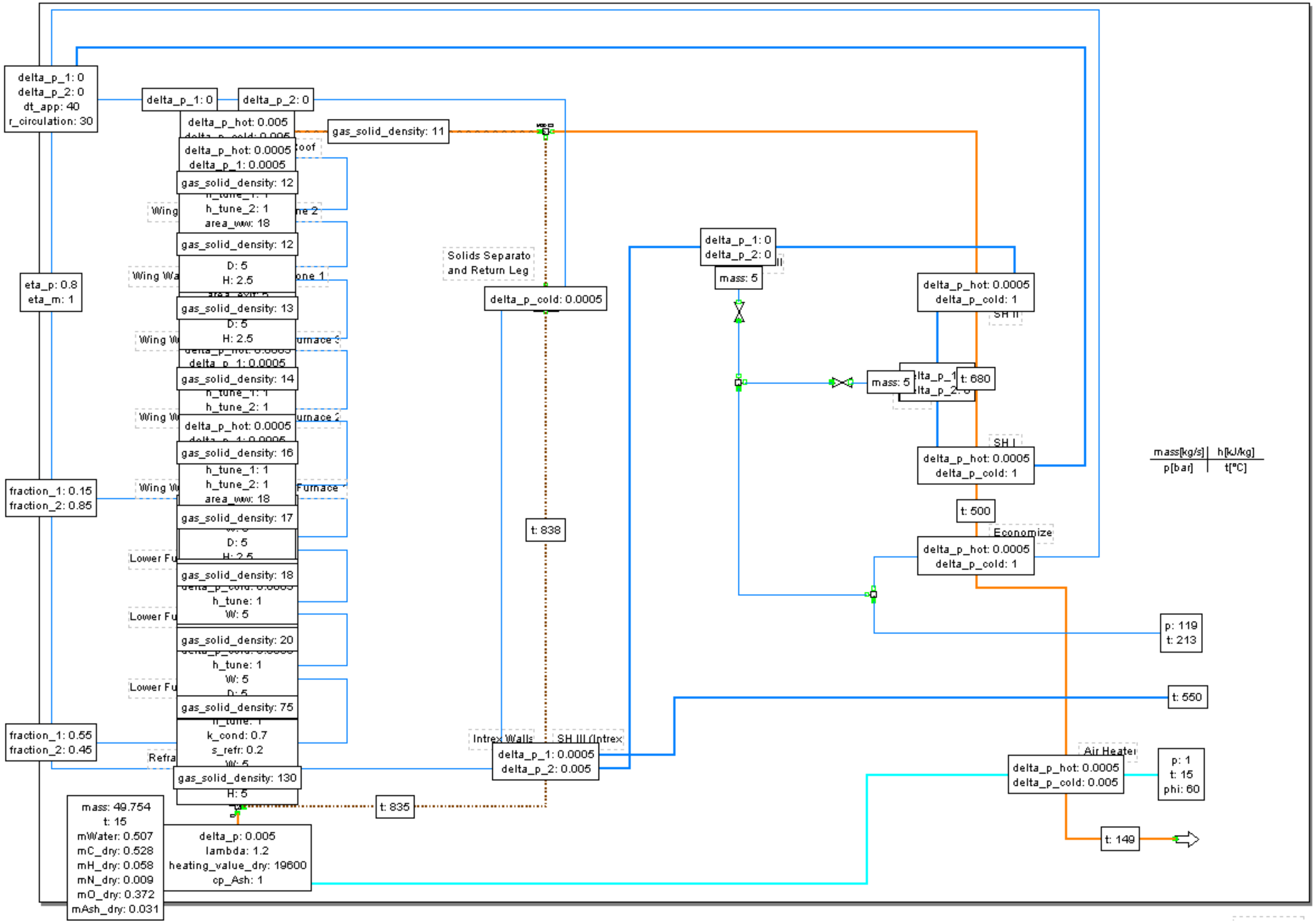


Figure 5.7. Boiler model with design-point values

The processes that are taken place in the boiler model can be described with two following paths – water-steam and air-combustion gas.

Water-steam path

At first, feed water is heated in the economizer. At the same time, a small amount of the feed water is used for desuperheating the steam after first and second superheaters - SH I and SH II – in order to control the outlet steam temperature. After economizer water with temperature of 283°C is fed to the water drum. From the drum water is led to the evaporative surfaces. The model represents a forced circulation boiler so a pump provides the driving force for the internal water-steam cycle. After the pump water flow is divided. 15% of water is directed to additional heat transfer surface – wing wall and 55% of the rest water flow is sent to the membrane walls of the boiler furnace. This part of the furnace is represented by sequential series of co-current heat exchangers. The rest of the water is led to the INTREX walls and then is heated in heat transfer surfaces of solids separator and return leg. Then all these streams of steam-water mixture are united and sent to the drum for water-steam separation. Saturated steam with the temperature of 323°C is heated in superheaters SH I, SH II and SH III (INTREX) to obtain the live steam temperature of 550°C. The live steam pressure is 115 bar.

Air-combustion gas path

The air is coming to the air heater from the atmosphere with the temperature of 15°C. In the air heater the air is heated to 302°C by flue gases and is introduced to the combustion chamber where it serves as the combustion air. The combustion processes take place with an excess air ratio of 1.2. Then combustion gases are mixed with the returned solids, and this mixture with temperature of 868°C passes all heat transfer surfaces in the furnace. Due to its high heat capacity flow, the temperature of the gas-solid suspension decreases slightly in the furnace. After the furnace the combustion gases and solids are separated in the solids separator. Then combustion gases with the temperature of 854°C go through the heat exchangers in the back-pass. The gases pass two superheaters, economizer and air heater. After all these heat transfer surfaces the flue gases with temperature of 149°C are sent to gas treatment procedures and then exhausted to the atmosphere.

The solid material after the cyclone is fed to the heat exchanger INTREX. It is represented by two-sided heat exchanger where water is evaporated at the walls and steam is superheated in the tubular heat exchanger. After it the solids are returned to the furnace and mixed with combustion gases.

During simulations the following parameters are kept constant. The values of parameters are presented in Table 5.3.

Table 5.3. Invariable boiler parameters during simulations

Parameter	Value
Feedwater temperature [°C]	213
Steam pressure [bar(a)]	115
Steam temperature [°C]	550
Excess air ratio [-]	1.2
Ambient air pressure [bar]	1
Ambient air temperature [°C]	15
Evaporation cycle mass flow [kg/s]	4290
Spray mass flow in DSH I [kg/s]	5

5.4 Simulation 1: Effect of fuel moisture

During this simulation the influence of water content in the fuel on boiler operation is investigated. Table 1.1 in Appendix 1 presents the values of considered parameters with dependence on fuel moisture content.

In order to maintain the required level of steam parameters, with the moisture content increasing the value of fuel power is kept constant. As result, fuel mass flow increases with moisture rising. At the same time, the quantity of produced steam decreases due to decreasing boiler efficiency. Figure 5.7 illustrates the dependency between moisture content and steam mass flow.

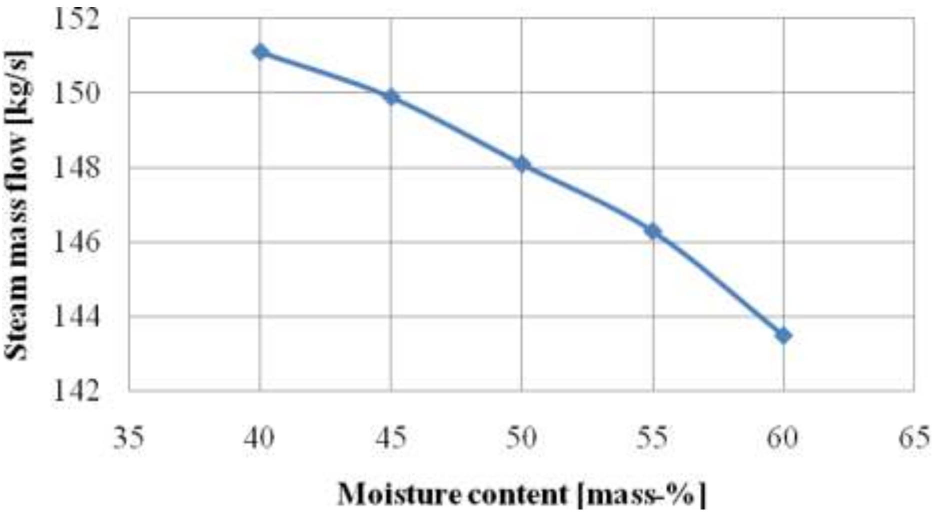


Figure 5.7. Dependence between steam mass flow and moisture content

The increasing level of fuel moisture results lower efficiency of combustion in the furnace of the boiler. The temperature of exhaust gases rises with the water fuel content. Figure 5.8 presents the dependence between the temperature of exhaust gases and fuel moisture.

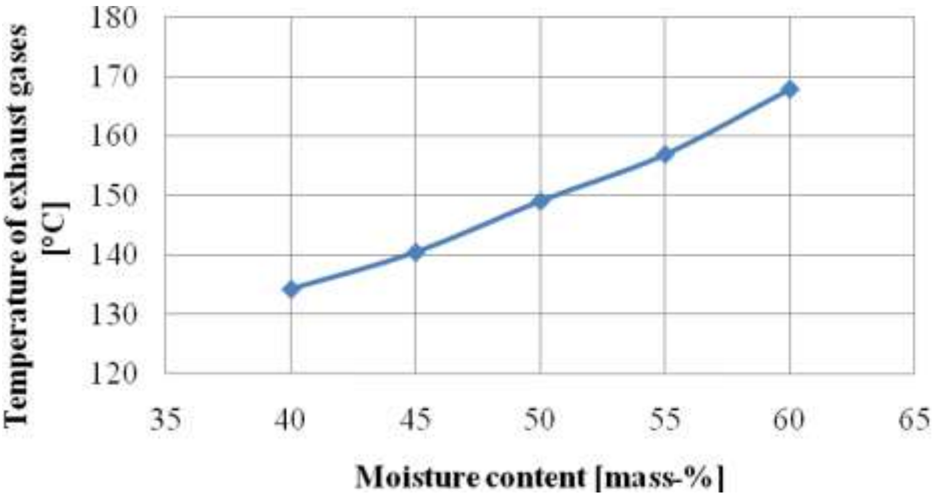


Figure 5.8. Dependence between exhaust gases temperature and moisture content

High moisture content results higher heat losses: for instance, losses with exhaust gases. In addition, efficiency of combustion decreases due to heat losses connected with fuel water evaporation. As a result of all aforementioned factors, the efficiency of boiler decreases with increasing of fuel moisture. Figure 5.9 illustrates the dependence between boiler efficiency and moisture content of the fuel.

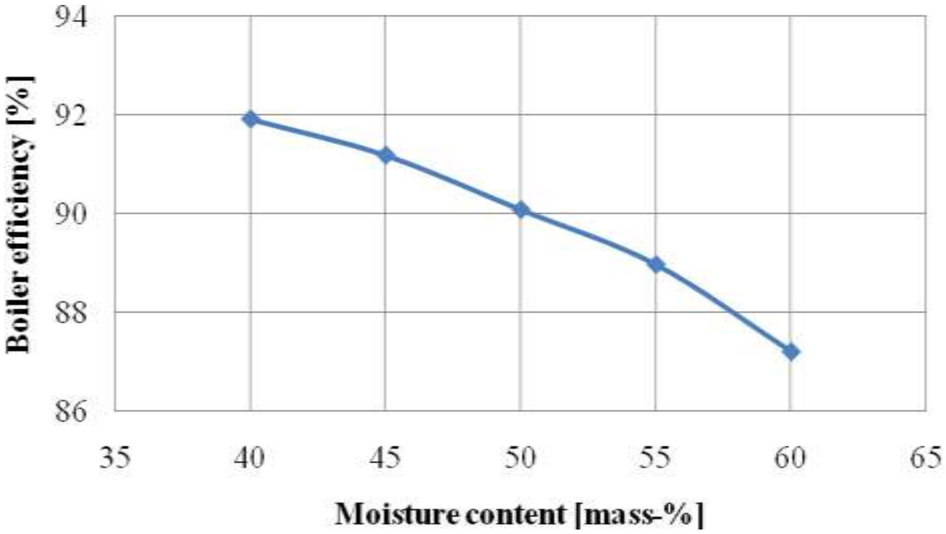


Figure 5.9. Dependence between boiler efficiency and moisture content

Heat transfer rate is also affected by fuel moisture content. Heat transfer in the furnace of the circulating fluidized bed boiler decreases with increasing of the fuel moisture. The influence of fuel water content on total heat transfer coefficients for each segment of the furnace is presented in the graphs in Appendix 1.

5.5 Simulation 2: Effect of boiler load

During simulation the influence of boiler load on operation is studied. The value of boiler load is changed from 100% to 80% with 5% step.

The character of suspension density distribution changes with the load. According to the suspension density profiles proposed by (Basu, 2006), profiles of density have been accepted. Figure 5.10 illustrates the accepted density profiles in the boiler furnace.

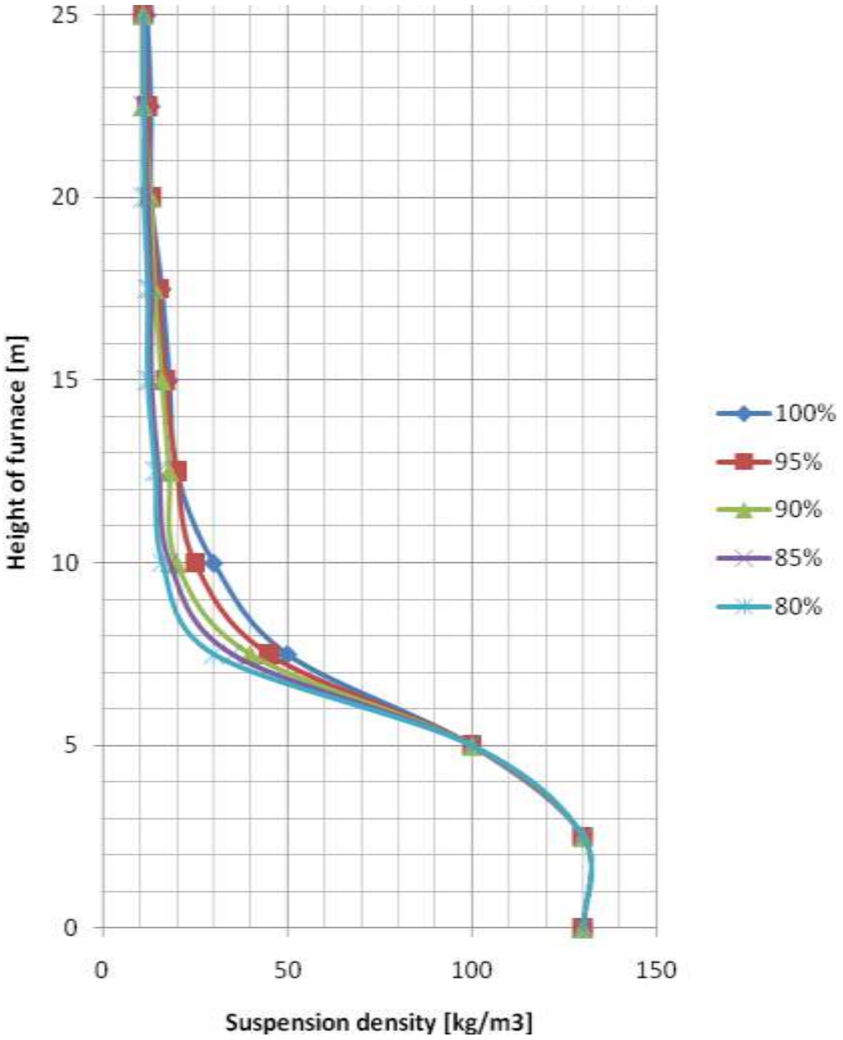


Figure 5.10. Dependency between suspension density distribution and boiler load rate

Table 2.1 in Appendix 2 presents the values of investigated parameters with dependence on boiler load.

Thermal power of the boiler decreases with the fuel mass flow decreasing. Figure 5.11 and Figure 5.12 present the character of fuel mass flow and fuel power decreasing with the boiler load.

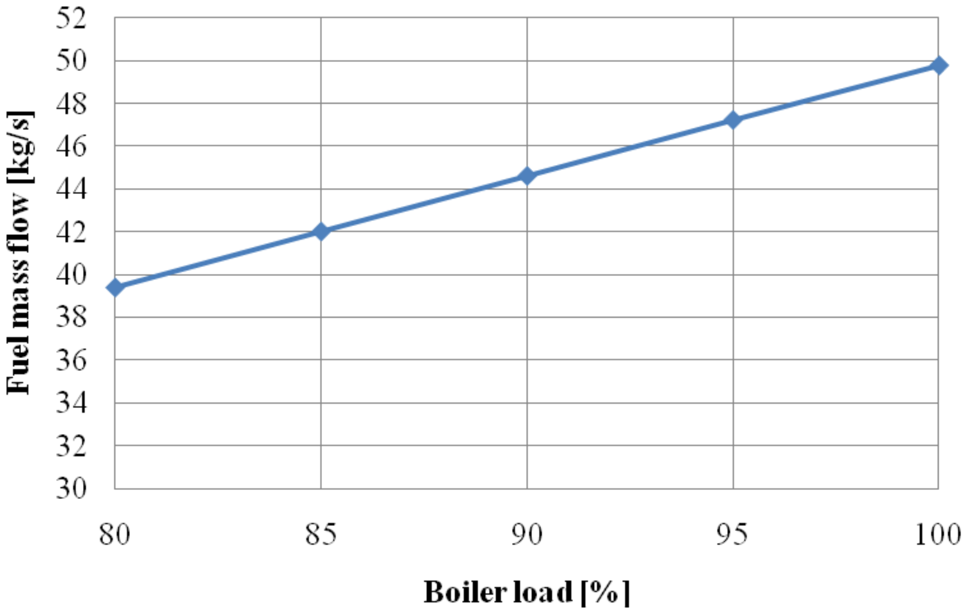


Figure 5.11. Dependency between fuel mass flow and boiler load

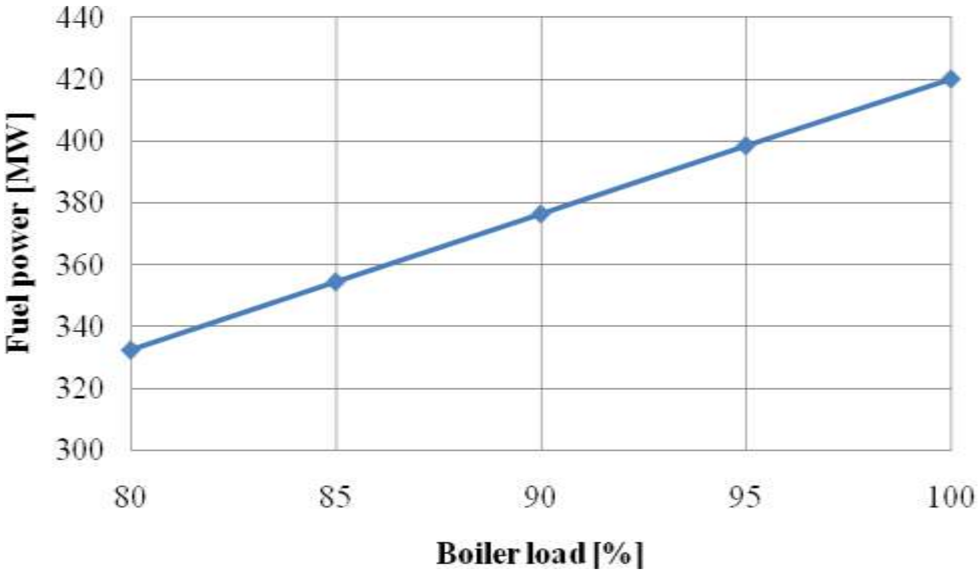


Figure 5.12 Dependency between fuel power and boiler load

As a result of boiler load reduction, the quantity of produced steam decreases. Figure 5.13 illustrates the dependency between steam flow rate and the load of the boiler.

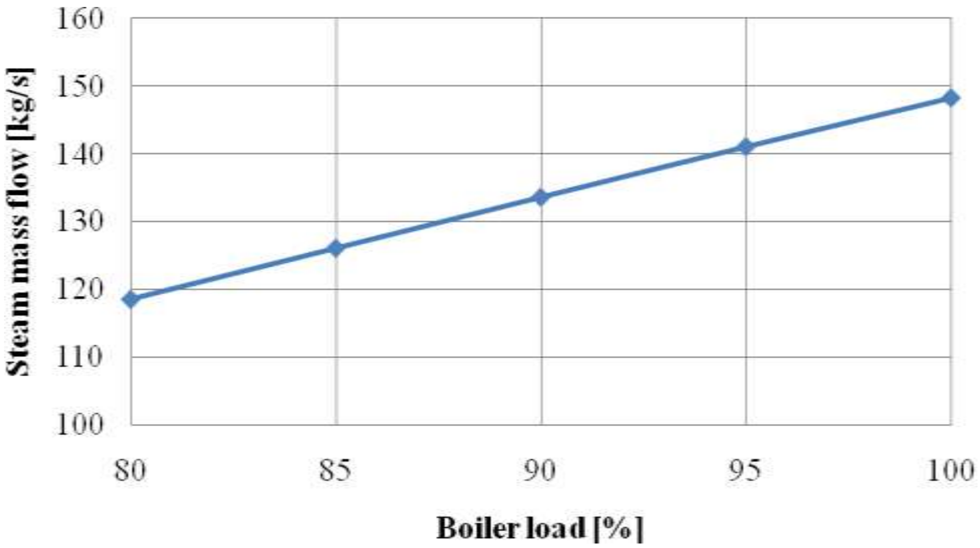


Figure 5.13. Dependency between steam mass flow and boiler load

As a result of decreasing the overall temperature level, temperature of combustion gases lowers. Figure 5.14 presents the character of exhaust gases temperature in dependence with boiler load.

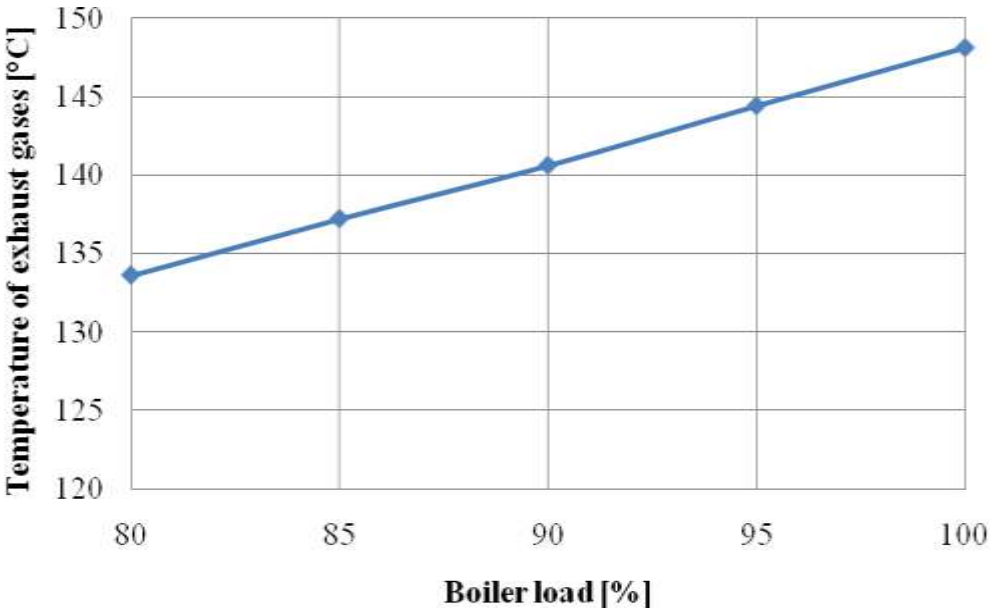


Figure 5.14. Dependency between exhaust gases temperature and boiler load

Due to exhaust gases temperature and mass flow reduction, the efficiency of the boiler slightly increases. The rate of heat transfer in the furnace decreases with the boiler load reduction. Graphs in Appendix 2 illustrate the character of total heat transfer coefficient variations in each part of the furnace.

6 CONCLUSION

Problems of climate changing and greenhouse gas emissions have incredible high significance. Complexity of mitigation appearing effects and management of causing processes forces humanity to search new technologies that will be able successfully replace present-day technologies. The requirements for such methods are rather high.

Bioenergy is one of the most challenging developing spheres of renewable energy technology. It represents extremely promising way of replacing some current technologies based on fossil fuels utilization.

In present work, main types, sources and properties of biomaterials were discussed. Woody and herbaceous biomass materials were chosen due to their advantageous of energy usage. Technical feasibility of utilization of these kinds of biomass in various energy generations is rather attractive and realizable.

Characteristics of woody and herbaceous types have many constitutive distinctions due to considerable difference in chemical composition in their wide range. Waste biomass, as for example animal wastes, municipal solid wastes, sewage sludge, differs considerably from aforementioned types of biomass and, discussion of its features was not concluded in a current work. Nevertheless, possibilities of utilization of various wastes may be rather beneficial in many cases.

In general, biomass fuels have lower heating values then fossil fuels, such as for instance coal. Moreover, high ash content of these fuels may cause problems during combustion process. High ash content of biomass materials result such effects as fouling, slagging and also possible bed agglomeration.

At the same time, such advantages, as significant diversity of available biomass feedstock, possible utilization in existing plants, and capability of depletion of harmful environmental impacts, make proper biomass utilization substantially profitable.

Among broad range of possible ways of biomass utilization, combustion represents one of the most spread and developed ways. In this paper, the attention was concentrated on circulating fluidized bed combustion. Combustion specific features have been discussed. Heat transfer nature of circulating fluidized bed combustion is described in various approaches by different models and equations. The most reliable models have been examined.

The majority of reported techniques is based on data obtained from laboratory-scale units and, as a result, cannot be easily implemented to large-scale units design. Simultaneously, many proposed models represent quite complicated systems that demand the knowledge of wide range of necessary parameters. The aim of current work was to develop model of CFB boiler with reasonable level of complexity.

IPSEpro software has been used for model development. During model creation some simplifications have been assumed. Derived model can be used for modeling boiler operation in design and off-design conditions. In off-design conditions various conditions may be realized. In this paper, effects of fuel moisture and boiler load have been studied. Developed model demands comparatively not high amount of necessary inputs that increases the level of model practical applicability. Moreover, IPSEpro program allows rather fast and accurate calculations of required parameters. As a result, current model can be successfully used for simulation of boiler operation.

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Appendix 1 Influence of fuel moisture on total heat transfer coefficients

Table 1.1. Simulation results of moisture content variation

Fuel moisture [-]	0.40	0.45	0.50	0.55	0.60
Fuel mass flow [kg/s]	38.89	43.31	49.75	56.05	65.72
Temperature of exhaust gases [°C]	134.28	140.47	149.05	156.88	167.84
Boiler efficiency [%]	91.91	91.18	90.08	88.97	87.21
Steam mass flow [kg/s]	151.11	149.9	148.1	146.3	143.5
LHV as fired [MJ/kg]	10.783	9.681	8.424	7.476	6.374
Total heat transfer coefficient [W/m^{2}K]					
Refractory	3.326	3.323	3.318	3.313	3.305
Lower furnace 1	386.133	384.097	381.208	378.496	374.432
Lower furnace 2	269.559	268.133	266.110	264.210	261.365
Lower furnace 3	260.886	259.508	257.554	255.718	252.967
Upper furnace 1	254.809	253.466	251.561	249.771	247.090
Upper furnace 2	245.320	244.029	242.198	240.477	237.899
Upper furnace 3	235.257	234.021	232.267	230.618	228.148
Exit zone 1	228.142	226.945	225.247	223.650	221.257
Exit zone 2	224.415	223.240	221.573	220.005	217.654
Roof	220.624	219.470	217.833	216.293	213.984
Wing wall 1	195.028	193.966	192.459	191.045	188.927
Wing wall 2	188.137	187.114	185.663	184.300	182.260
Wing wall 3	180.815	179.833	178.441	177.132	175.173

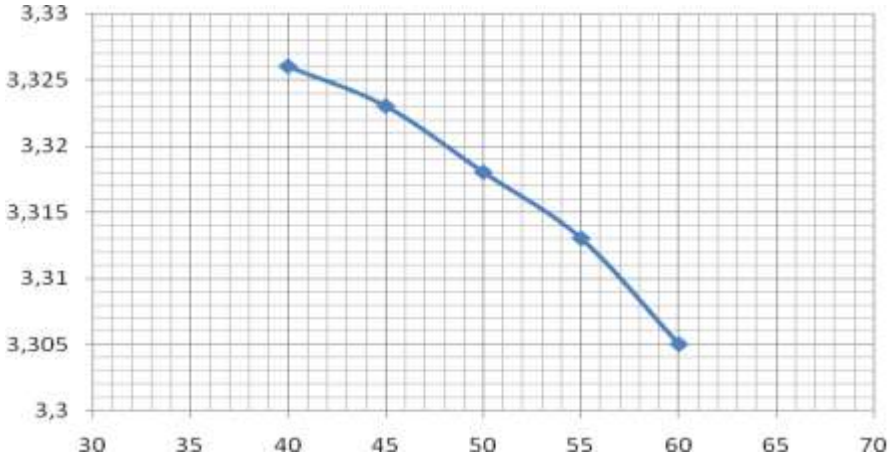
Wing wall 4	175.627	174.674	173.324	172.055	170.154
Wing wall 5	172.902	171.967	170.640	169.393	167.524
Heat transfer rate [MW]					
Refractory	0.191	0.187	0.181	0.175	0.167
Lower furnace 1	11.041	10.749	10.343	9.971	9.431
Lower furnace 2	7.673	7.468	7.185	6.926	6.550
Lower furnace 3	7.409	7.212	6.939	6.689	6.326
Upper furnace 1	7.220	7.028	6.763	6.519	6.166
Upper furnace 2	6.932	6.748	6.493	6.260	5.921
Upper furnace 3	6.629	6.453	6.210	5.987	5.662
Exit zone 1	5.771	5.618	5.407	5.212	4.930
Exit zone 2	5.665	5.515	5.308	5.117	4.841
Roof	3.089	3.007	2.894	2.791	2.640
Wing wall 1	1.989	1.936	1.863	1.795	1.697
Wing wall 2	1.914	1.863	1.792	1.727	1.633
Wing wall 3	1.834	1.785	1.718	1.655	1.565
Wing wall 4	1.777	1.730	1.664	1.604	1.517
Wing wall 5	1.746	1.699	1.635	1.576	1.490
Solid separator and Return leg	137.47	134.554	130.554	126.840	121.385
INTREX	2.201	2.1567	2.094	2.036	1.951
SH I	54.008	55.192	56.795	58.110	59.745

SH II	58.634	58.198	57.261	56.270	54.624
SH III (INTREX)	23.692	22.886	21.753	20.698	19.142
Economizer	42.338	44.115	46.623	48.907	52.173
Air heater	51.070	53.282	56.744	59.497	64.114

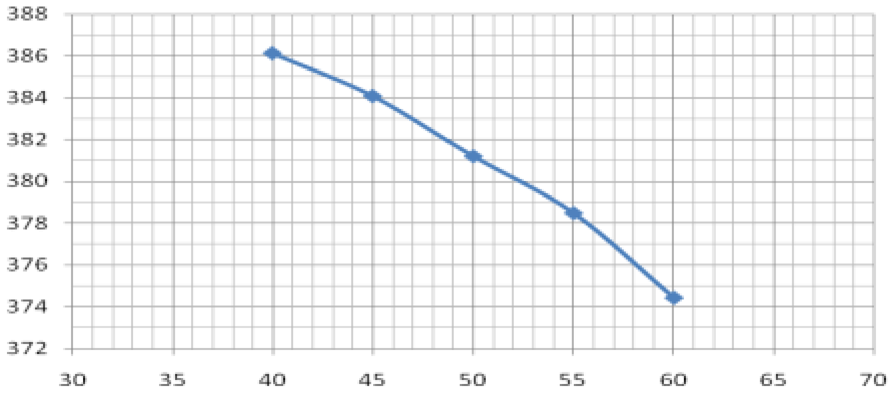
X-axis: Fuel moisture [%]

Y-axis: Total heat transfer coefficient [W/m^{2}K]

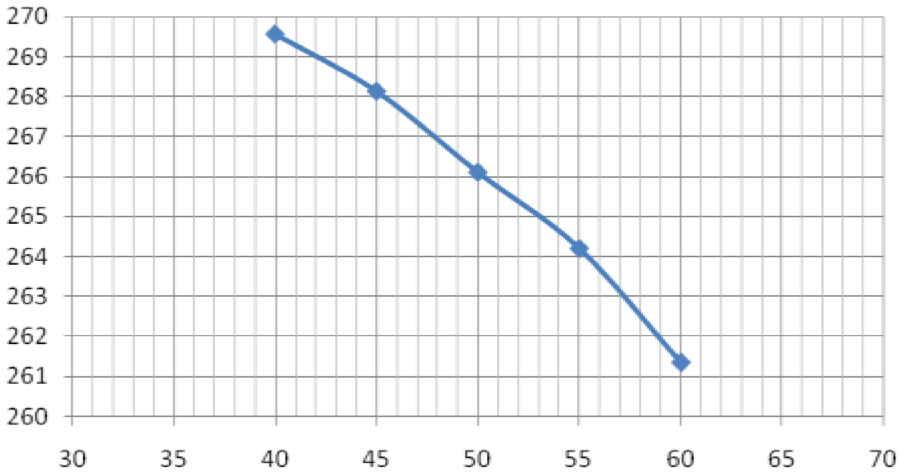
Appendix 1.1. Refractory



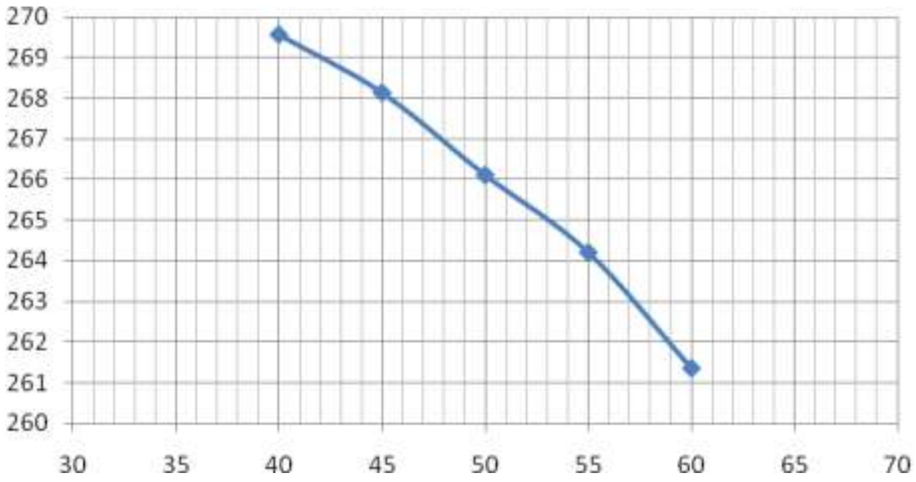
Appendix 1.2. Lower furnace 1



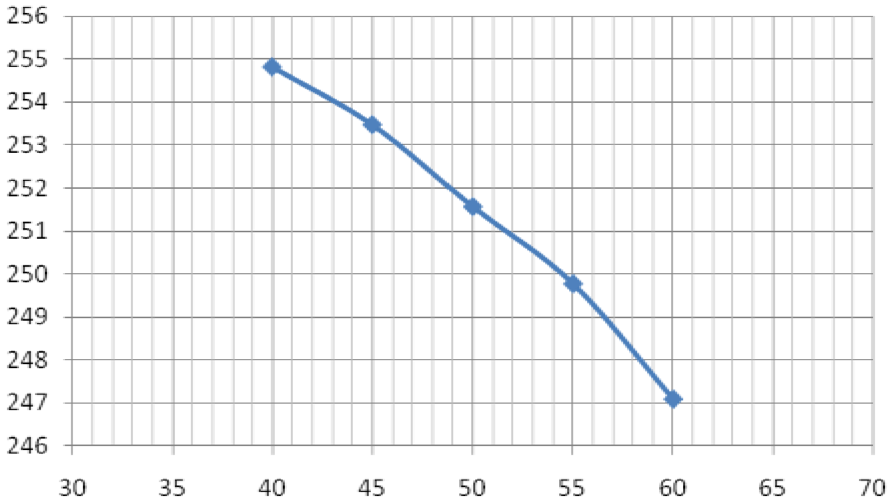
Appendix 1.3. Lower furnace 2



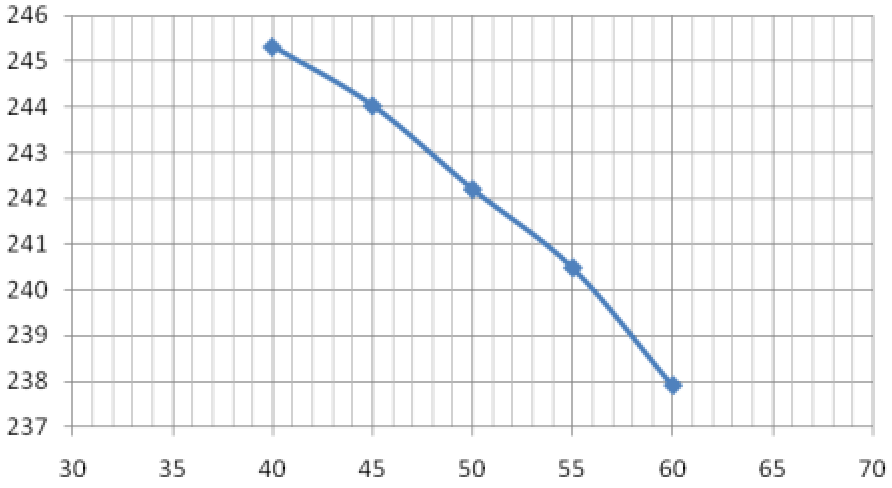
Appendix 1.4. Lower furnace 3



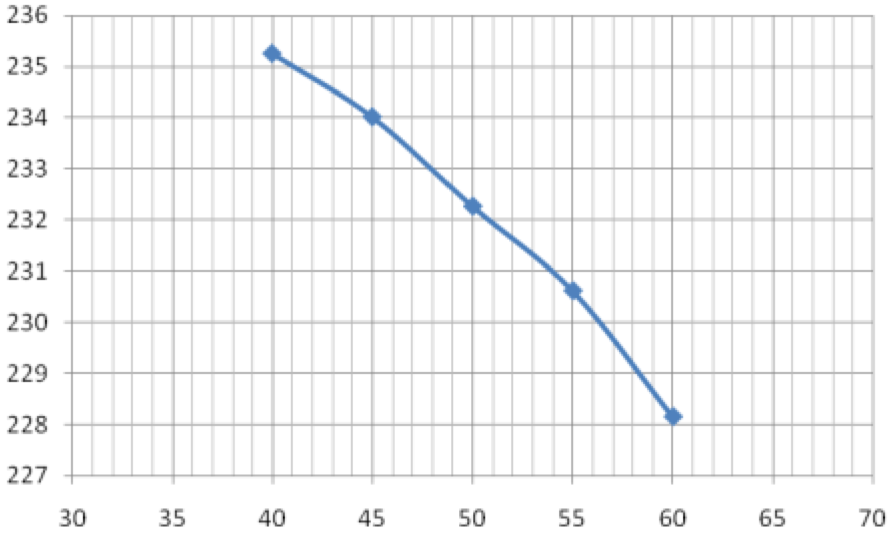
Appendix 1.5. Upper furnace 1



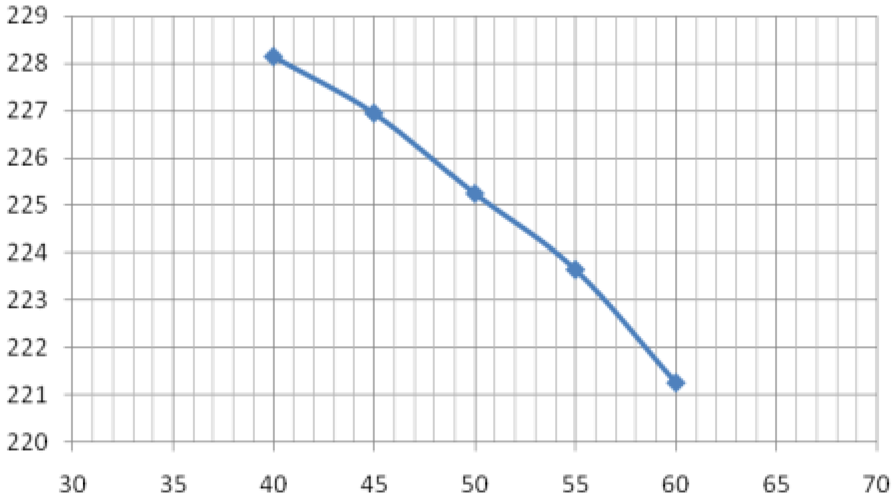
Appendix 1.6. Upper furnace 2



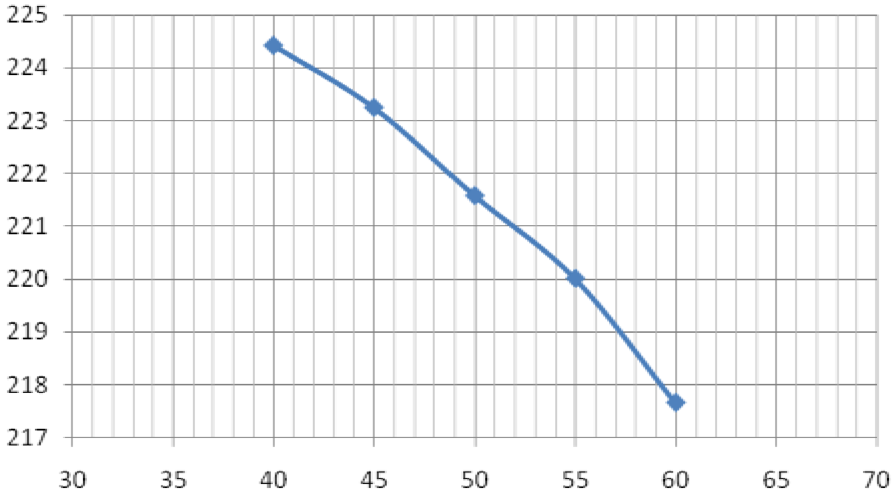
Appendix 1.7. Upper furnace 3



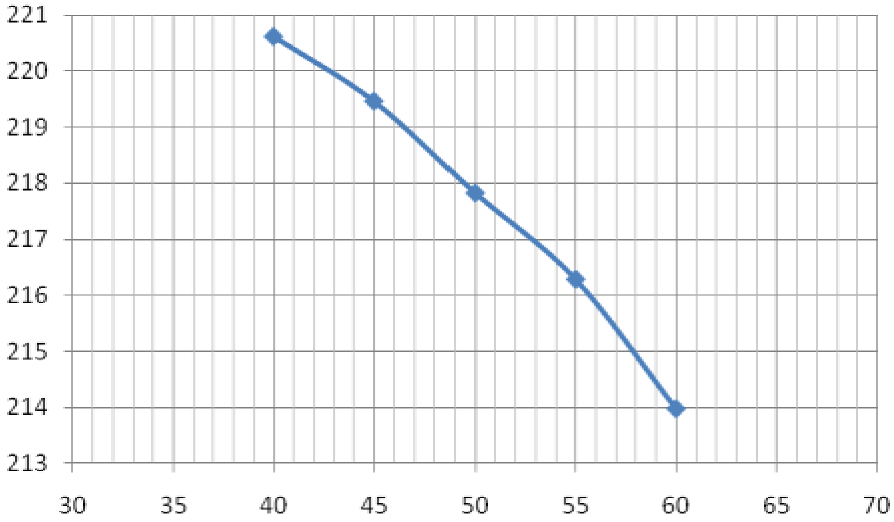
Appendix 1.8. Exit zone 1



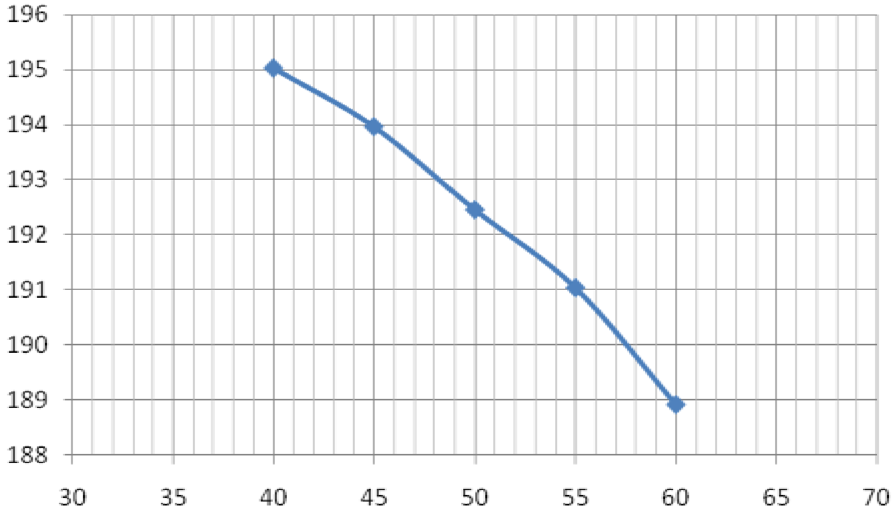
Appendix 1.9. Exit zone 2



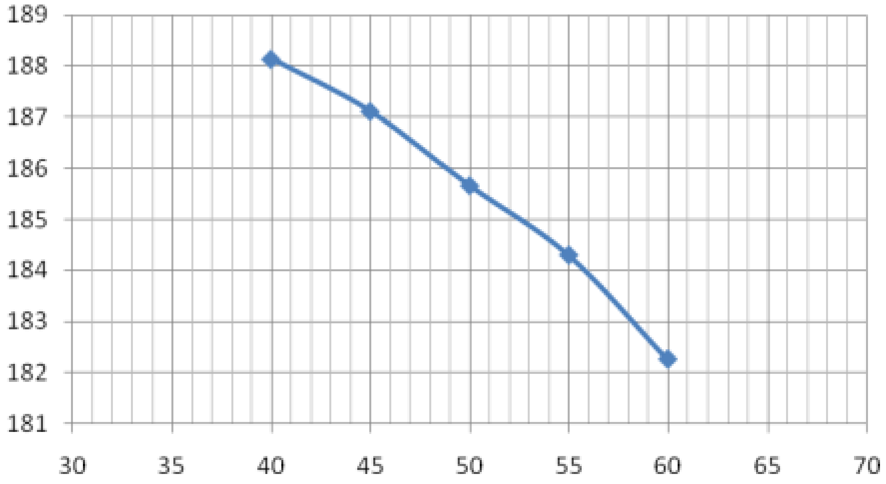
Appendix 1.10. Roof zone



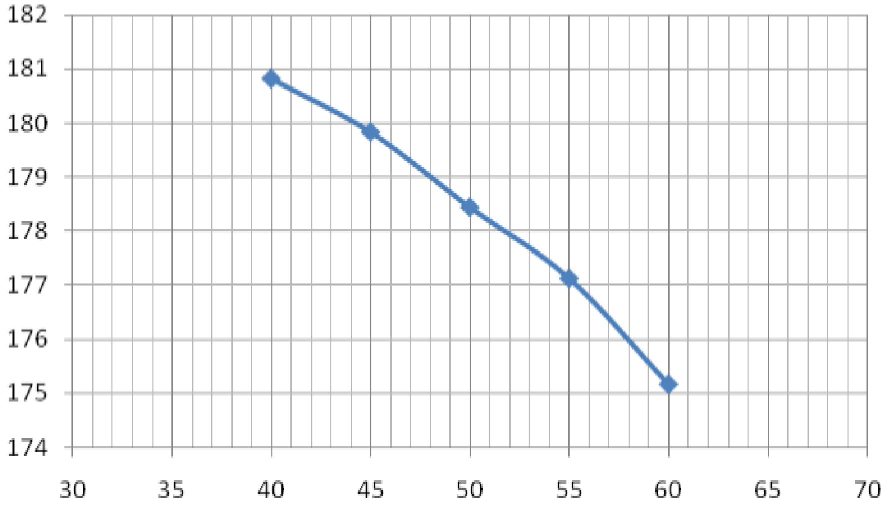
Appendix 1.11. Wing wall 1



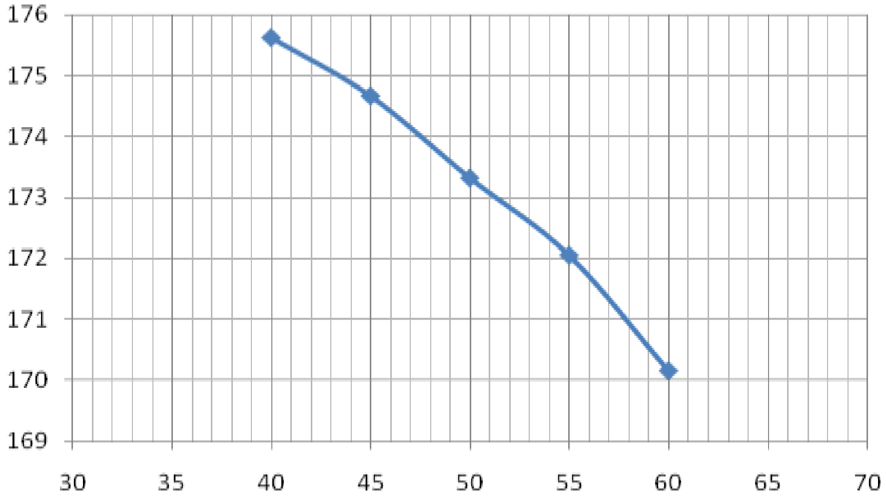
Appendix 1.12. Wing wall 2



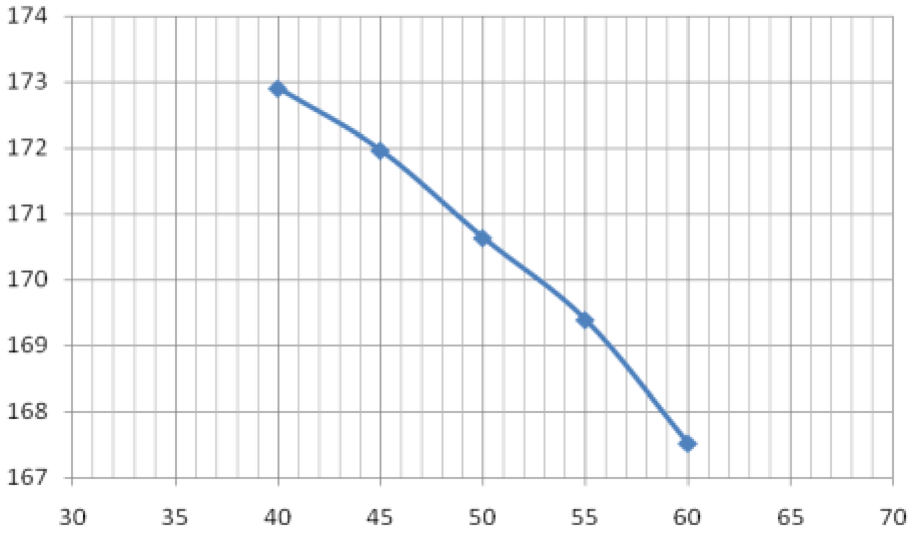
Appendix 1.13. Wing wall 3



Appendix 1.14. Wing wall 4



Appendix 1.15. Wing wall 5



Appendix 2 Influence of boiler load on total heat transfer coefficients

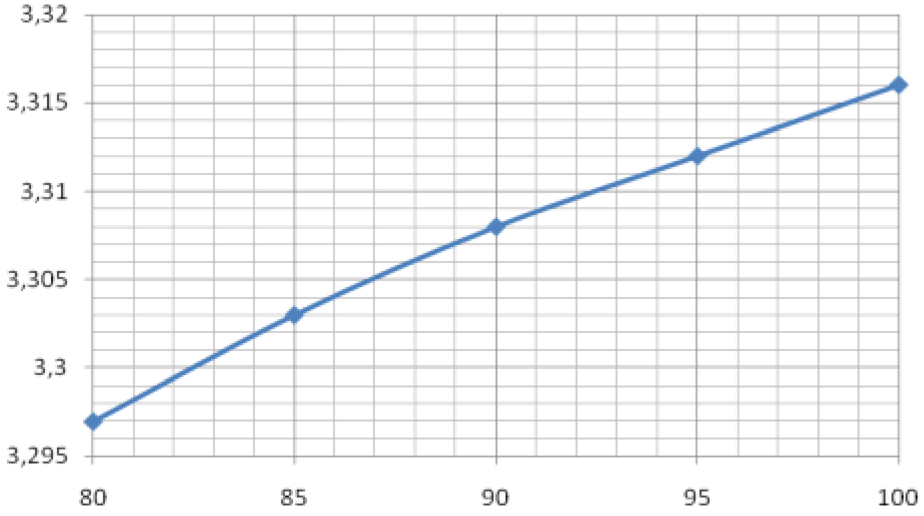
Table 2.1. Simulation results of boiler load variation

Boiler load [%]	100	95	90	85	80
Thermal power [MW]	381.1	362.5	343.4	324.2	305.1
Fuel power [MW]	419.9	398.4	376.4	354.5	332.5
Fuel mass flow [kg/s]	49.754	47.21	44.60	42.01	39.4
Temperature of exhaust gases [°C]	148.1	144.4	140.6	137.2	133.6
Steam mass flow [kg/s]	148.2	141.02	133.6	126.1	118.6
Boiler efficiency [%]	90.1	90.3	90.5	90.7	90.9
Total heat transfer coefficient [W/m^{2}K]					
Refractory	3.316	3.312	3.308	3.303	3.297
Lower furnace 1	453.959	445.615	436.735	427.745	418.297
Lower furnace 2	354.704	334.823	313.167	296.349	278.225
Lower furnace 3	294.884	281.436	261.690	245.961	235.138
Upper furnace 1	264.671	260.494	250.381	230.465	222.157
Upper furnace 2	253.244	245.928	238.456	223.730	215.155
Upper furnace 3	237.792	233.239	228.456	220.192	215.042
Exit zone 1	227.712	222.972	221.539	216.580	211.362
Exit zone 2	227.630	219.330	214.294	212.884	207.597
Roof	224.088	215.625	210.515	209.126	207.529

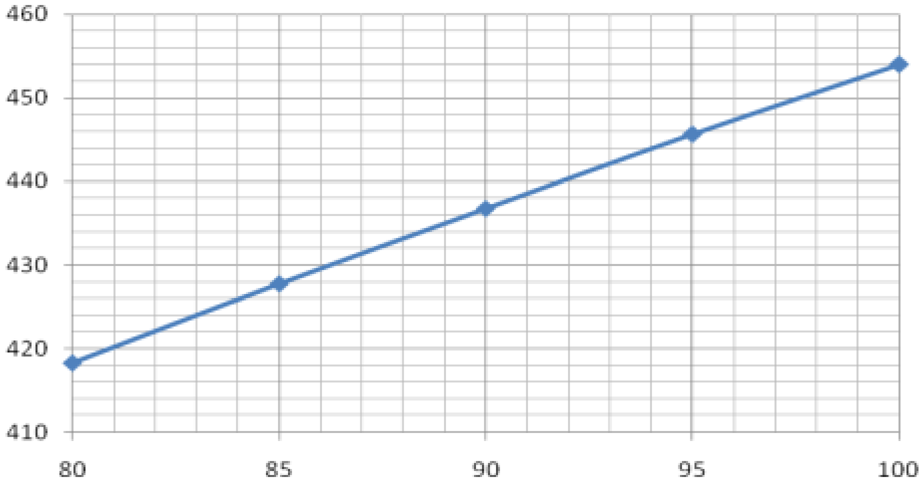
Wing wall 1	201.861	198.751	191.333	176.794	170.643
Wing wall 2	193.593	188.205	182.528	171.891	165.539
Wing wall 3	182.384	178.991	175.417	169.308	165.450
Wing wall 4	175.051	171.516	170.378	166.670	162.760
Wing wall 5	174.986	168.857	165.091	163.970	160.007
Heat transfer rate [MW]					
Refractory	0.177	0.174	0.169	0.164	0.159
Lower furnace 1	12.118	11.639	11.108	10.586	10.029
Lower furnace 2	9.432	8.705	7.922	7.291	6.627
Lower furnace 3	7.811	7.288	6.593	6.023	5.574
Upper furnace 1	6.988	6.724	6.290	5.624	5.248
Upper furnace 2	6.668	6.327	5.965	5.444	5.067
Upper furnace 3	6.242	5.982	5.703	5.344	5.053
Exit zone 1	5.366	5.132	4.964	4.719	4.458
Exit zone 2	5.356	5.037	4.788	4.627	4.367
Roof	2.925	2.747	2.609	2.521	2.422
Wing wall 1	1.919	1.847	1.730	1.553	1.451
Wing wall 2	1.835	1.743	1.645	1.506	1.403
Wing wall 3	1.723	1.653	1.576	1.479	1.399
Wing wall 4	1.650	1.579	1.527	1.453	1.373
Wing wall 5	1.647	1.551	1.476	1.426	1.347
Solid separator and Return leg	128.412	125.007	121.535	118.056	114.130
INTREX	2.063	2.003	1.945	1.886	1.820
SH I	55.668	51.607	47.482	43.855	40.210
SH II	56.657	53.658	50.575	46.850	42.961
SH III (INTREX)	21.174	20.144	19.093	18.096	16.962
Economizer	45.921	42.657	39.372	36.406	33.453
Air heater	56.069	52.373	48.663	45.168	41.705

X-axis: Boiler load [%]
Y-axis: Total heat transfer coefficient [W/m^{2}K]

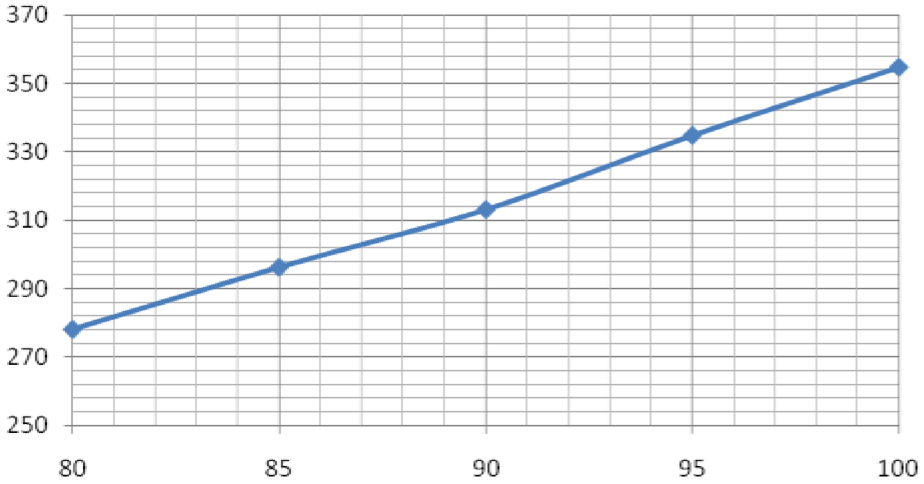
Appendix 2.1. Refractory



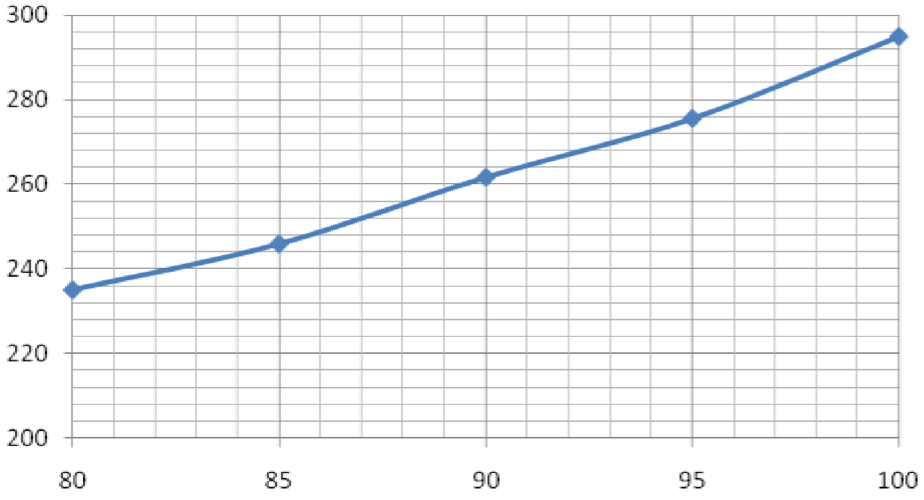
Appendix 2.2. Lower furnace 1



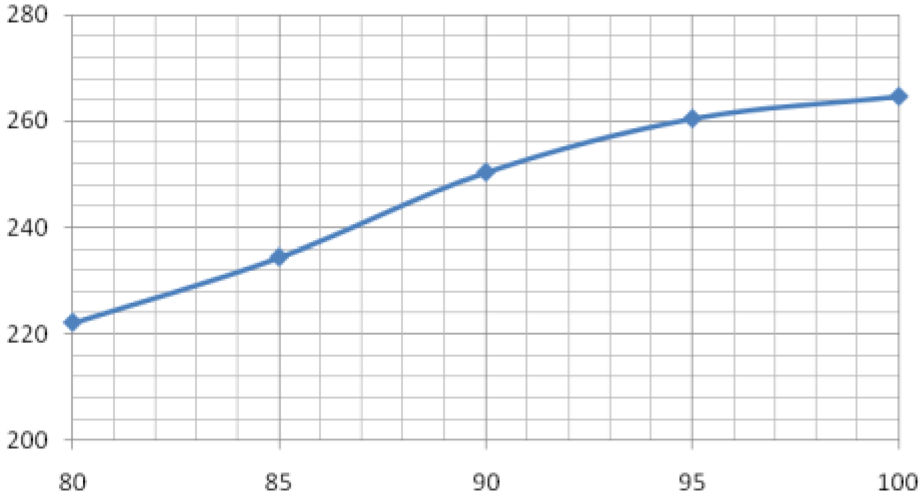
Appendix 2.3. Lower furnace 2



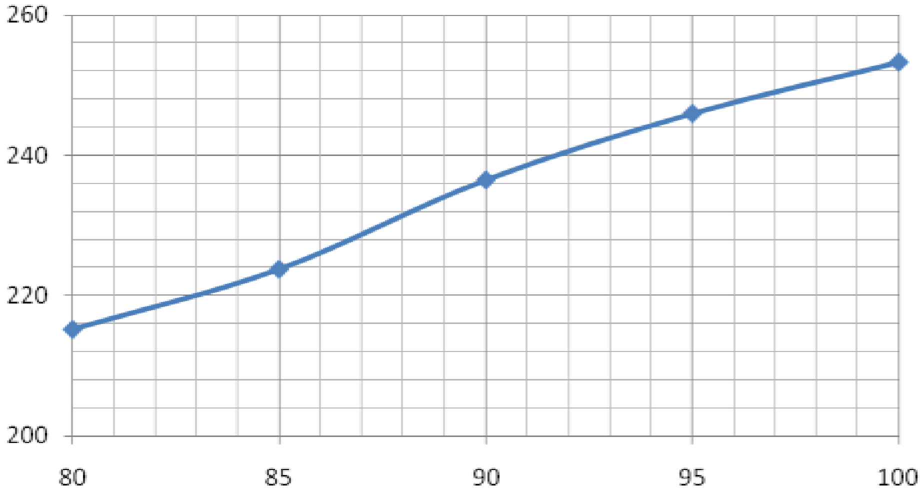
Appendix 2.4. Lower furnace 3



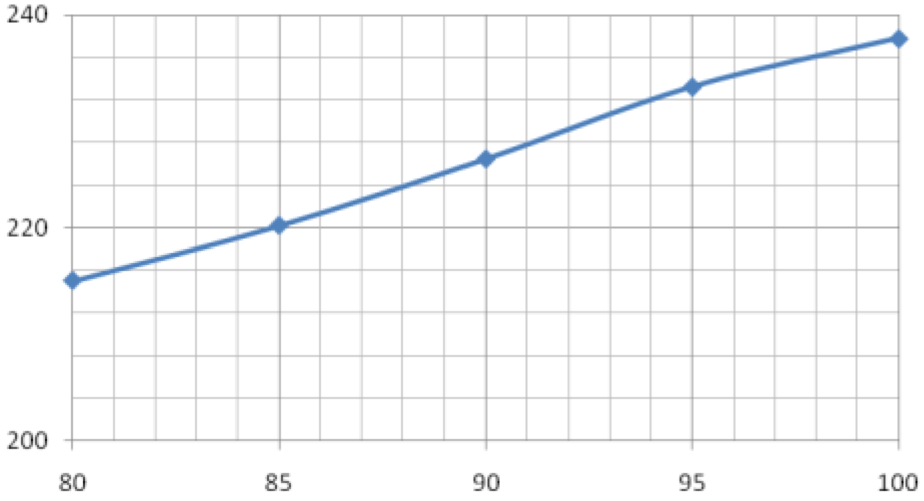
Appendix 2.5. Upper furnace 1



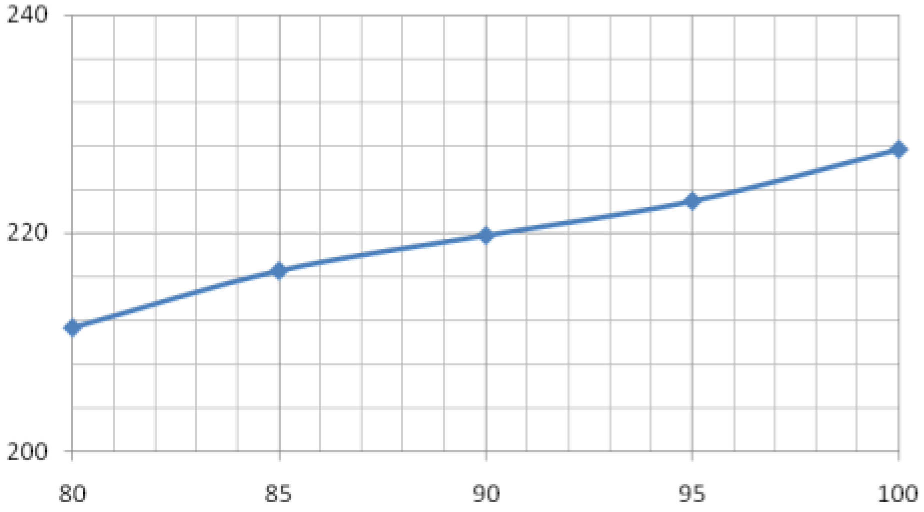
Appendix 2.6. Upper furnace 2



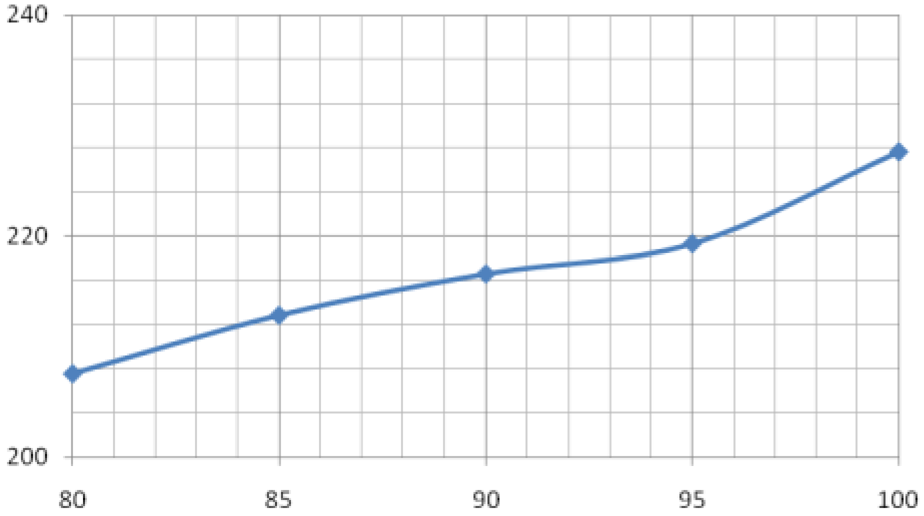
Appendix 2.7. Upper furnace 3



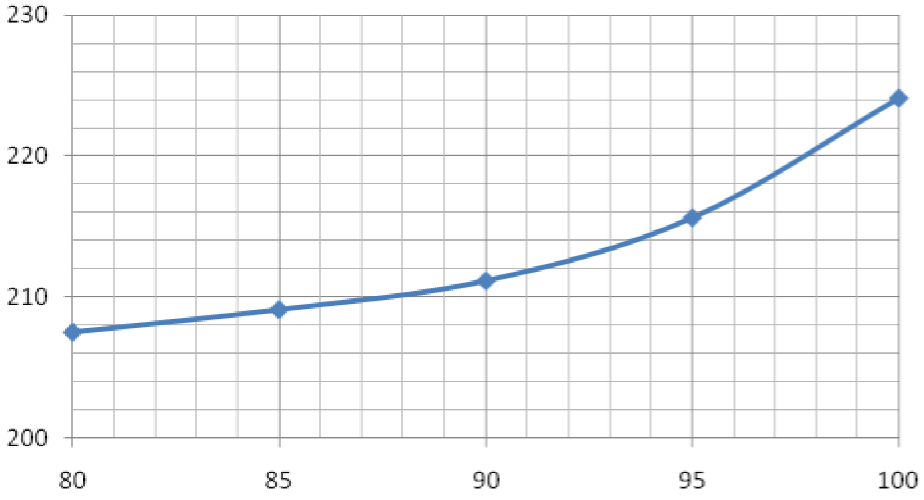
Appendix 2.8. Exit zone 1



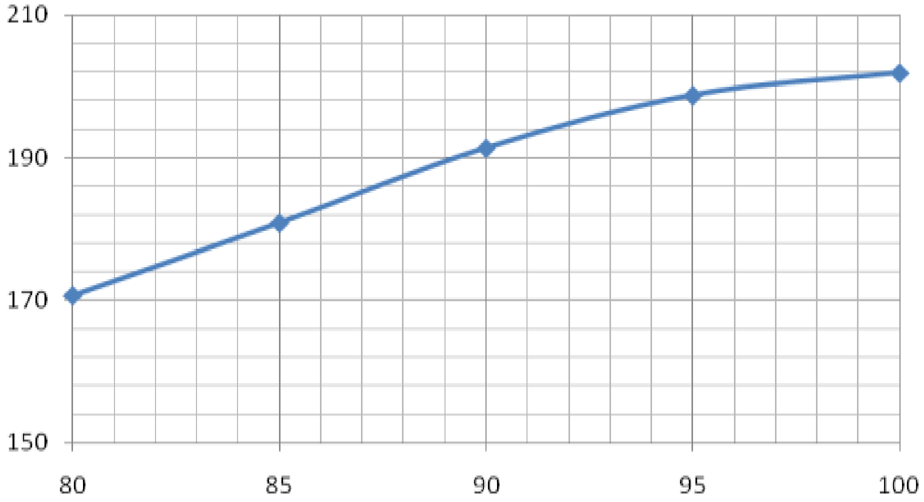
Appendix 2.9. Exit zone 2



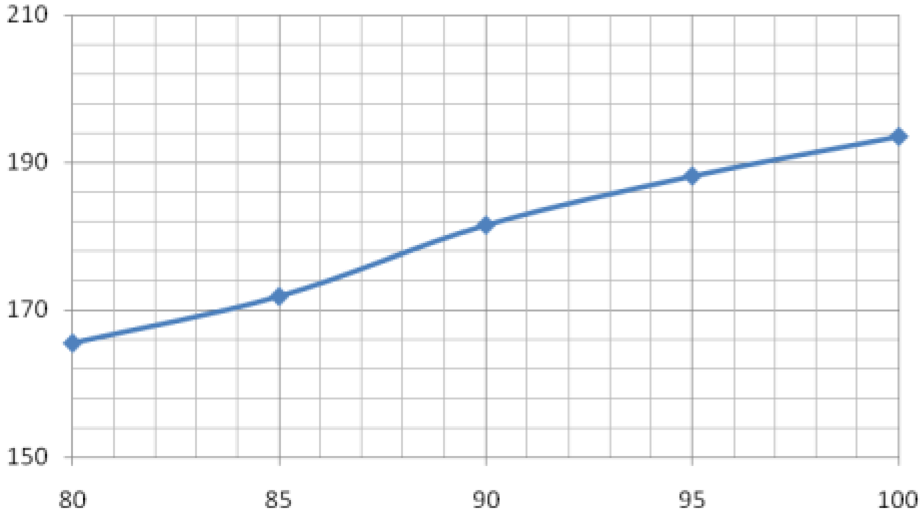
Appendix 2.10. Roof zone



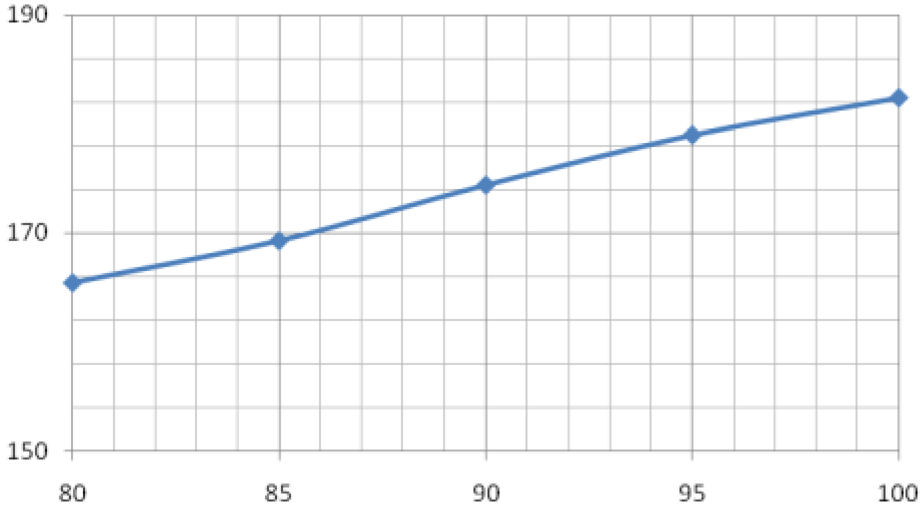
Appendix 2.11. Wing wall 1



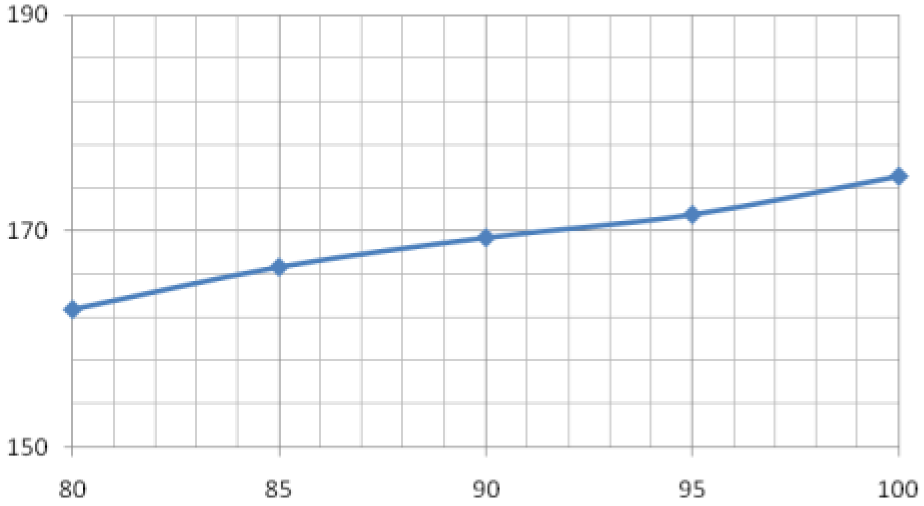
Appendix 2.12. Wing wall 2



Appendix 2.13. Wing wall 3



Appendix 2.14. Wing wall 4



Appendix 2.15. Wing wall 5