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Modeling, Simulation, and Validation with Measurements of a Heat Recovery Hot Gas Cooling Line for Electric Arc Furnaces

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Waste heat recovery has a high potential for increasing the efficiency and sustainability of electric arc furnaces. In the present work, a dynamic model of a water cooled hot gas line is presented and validated with measurements of a newly installed electric arc furnace (EAF) with a waste heat recovery system. Due to necessary reconstruction work of the EAF, the cooling pass is upgraded to a heat recovery hot gas line. With hot water from the hot gas line saturated steam can be produced and fed into the existing steam net. The heart of the system is the water cooled hot gas line which is responsible for sufficient hot gas cooling on the one hand and adequate hot water generation for the steam generators on the other hand. The water cooled hot gas line is modeled in the commercial simulation software APROS and validated with measurements of the performance test during commissioning of the heat recovery plant. The simulation results are showing an excellent agreement to the measurements. The results embody that the model is both very reliable to estimate the transient behavior of the hot gas line and able to predict the operational process conditions.

1. Introduction

The iron and steel industry, as one of the biggest emitters of anthropogenic carbon dioxide, contributes a significant share of the annual worldwide greenhouse gas emissions.[1] Due to unusually low costs for primary energy and emission certificates in the recent years, steel plant operators did not have any incentive to reduce their energy demand and their carbon dioxide emissions. Increasingly stringent environmental standards and the omnipresent possibility of rising primary energy costs force steel plant operators to rethink the possibilities of energy demand and emission reduction. The investment costs for new turnkey low-CO_2 steel making processes, such as hydrogen steel making, would lead to a substantial market price increase and would be hard to recoup under the prevailing steel market conditions.[2] Considering the high investment cost for new technologies, a promising approach for taking a huge step toward environmentally conscious production is waste heat recovery. With intelligent utilization concepts it is possible to reduce the primary energy demand on the one hand and to reduce greenhouse gas emission on the other hand.

Electric arc furnaces are using both electrical and chemical energy for melting and refining steel scrap. The residual energy input can be assigned to the exothermic chemical reactions in the steel bath. Many investigations are dealing with the reduction of the energy consumption by, for example, oxygen blowing, oxy-fuel burners, or using ultra-high power transformers.[3] As measurements of the considered EAF showed, nearly 34% (see **Figure 1**) of the total energy input leaves the electric arc furnace with the off-gas and is dissipated via the cooling water to the environment. The hot off-gas shows typical volume flows of approximately 150 000 $Nm^3\ h^{-1}$ and temperature peaks of 1250 °C, as off-gas measurements of the considered electric arc furnace show in **Figure 2**. Considering the high volume flow and the high temperatures the off-gas is appropriate for heat recovery applications. Utilizing the recovered heat as saturated steam for the steam net makes a heat recovery hot gas line very interesting for plant operators.

Many investigations on improving the energy performance of electrical steel plants are aiming on electricity production with, for example, Organic Rankine Cycles.[4] Due to the high investment costs for power blocks and the low revenues for selling electricity, electricity production with heat recovery plants is often not economically feasible. Another possibility to

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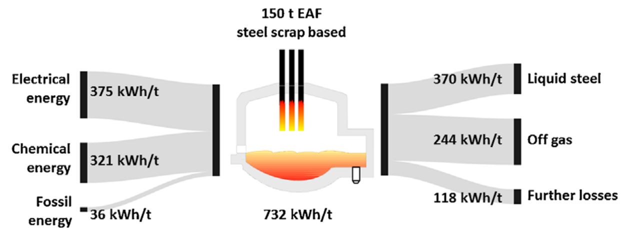

Figure 1. Sankey diagram of the revamped 150 t electric arc furnace.

decrease the demand for electricity is preheating of the scrap, charged to the electric arc furnace.[5]

In ref.,[6] a heat recovery concept for electric arc furnaces, whereby the heat is utilized as electricity and combined heating, is introduced. Within this concept, steam accumulators are smoothing the fluctuations.

A phase change material based heat recovery approach is investigated in ref.[7] The phase change material smooths temperature peaks of the off-gas already on the gas side of the heat recovery concept.

The adopted approach in ref.[3,8] is mainly the reduction of energy consumption of the furnace with, for example, oxygen blowing or carbon injection. In ref.[9,10] the environmental impact of electric steelworks is investigated. Simulations showed a reduction of the environmental impact, depending on the quality of the used steel scrap.

A heat recovery approach for steam production, similar to the approach introduced in this investigation, is presented in ref.[11] The smoothing of the fluctuations is performed by steam accumulators and steam is generated for the plant heating network and feed water preheating.

To address the known issues regarding fluctuations and proper utilization option, a novel heat recovery approach is introduced. With the novel approach, saturated steam for pickling lines is generated with pressurized water as heat transfer fluid and a thermocline storage tank as thermal energy storage. Hence, the steam can be utilized directly and installed fossil fuel fired steam generators can be substituted. There is no such waste heat recovery and utilization plant, like the one presented in this work, which has been realized up to now.

2. EAF Off-Gas Heat Recovery

The first component of state-of-the-art electric arc furnace dedusting systems is the water cooled hot gas line. The thermal energy of the off-gas is transferred to the environment via cooling water and cooling towers to meet the temperature requirements of the bag filters downstream of the hot gas line. A novel approach is to recover the former dissipated energy and utilize it inside the steel plant for example as saturated steam or electric energy. The recovered thermal energy is utilized directly as saturated steam within the steel plant. The thermal energy of the hot off-gas is transferred to the heat transfer fluid and is buffered in thermal energy storage. Pressurized water acts thereby as heat transfer fluid within this concept. The necessity of thermal energy storage arises from the fluctuating off-gas temperature and volume flow as it can be seen in Figure 2. The thermocline storage concept is a well-established concept and often used in various industry sectors and therefore it meets the demands for the presented heat recovery approach perfectly. The capacity of the thermal energy storage is designed in order to meet constant steam production with the steam generators. The steam net and the steam consumers require relatively constant operation conditions. Subsequently well-designed thermal energy storage is vital for the heat recovery concept.

The process diagram of the introduced heat recovery approach can be seen in **Figure 3**. During periods with a surplus of thermal energy at the hot gas line, the thermocline storage is charged and hot water is pumped to the steam generator simultaneously. Inversely, during idle times of the electric arc furnace, the steam generator is supplied with hot water from the thermocline storage only and the storage is discharged. The hot water from the storage is used to produce saturated steam in a shell and tube heat exchanger for the integrated steam net at the site. In case of less or no steam production at the steam generators, an additional heat exchanger is installed in order to ensure continuous electric arc furnace production. The detailed flow sheet of the modeled heat recovery hot gas line is shown in **Figure 4**. The cooling pass starts with the fixed elbow where the highest off-gas temperatures occur, expectedly. The drop out box is the second part of the hot gas line and connects the fixed elbow with the horizontal components of the heat recovery cooling

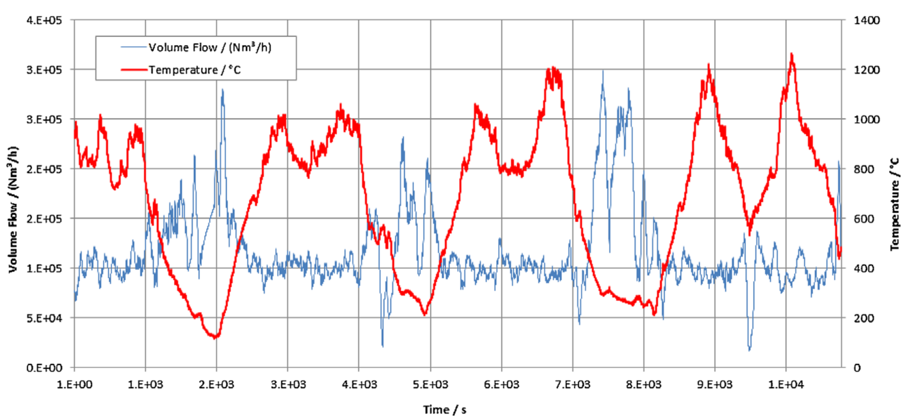

Figure 2. Temperature and volume flow measurements of the considered EAF.

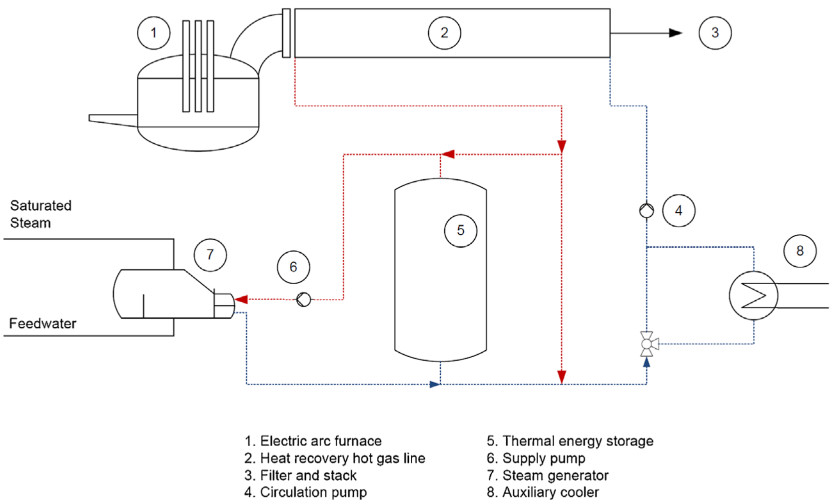

Figure 3. Flow sheet of the novel heat recovery approach for electric arc furnaces.

3. Experimental Section

The water cooled hot gas line is modeled and simulated with the commercial simulation software Advanced Process Simulation Software (APROS). APROS is a dynamic process simulation software which is developed by VTT Technical Research Centre of Finland Ltd and Fortum Power and Heat Oy. The software offers solution algorithms and wide model libraries for several industrial applications from nuclear power plant to pulp and paper applications to combustion processes. The software was developed initially for safety analysis at nuclear power plants and therefore expects highly detailed input data, for example, tube diameter, wall thickness, valve driving times, and characteristic head curves of pumps. To gather convincing dynamic simulation results a previous design calculation according to applicable guidelines is necessary. Prior the transient process simulation, a steady state model validation with the commercial software Power Plant Simulator & Designer (PPSD, former known as KED) has been performed. Due to the lack of sufficient gas side heat transfer correlations, the APROS model has been modified in order to comply with the steady state simulation results of PPSD. After the transient process simulation has been finished, the simulation results are validated against measurements of the erected heat recovery plant.

system. Within the drop out box the coarse dust is separated by gravitation. The following sections of the horizontal duct are cooling the hot gas to designed outlet conditions. The drop out box is constructed as a box with a rectangular cross section and a water cooled roof. The tubes are arranged in a meandering shape. The sectional water mass flow is distributed in tubes aligned at the outer diameter of the hot gas line and guided in a meandering shape along the section wall. The modeled meandering membrane wall segments of the hot gas line can be seen in **Figure 5**. The dynamic behavior of the system, in consideration of storage capacities of the materials, plays a highly relevant role for the design calculations. High flow velocities on the gas side as well as high dust loads, depending on the load case of the electric arc furnace, are design challenges. These challenges have been addressed by an appropriate heat exchanger design according to applicable guidelines such as the VDI-Heat Atlas.[12] Different load cases as well as load changes and temperature gradients have been investigated during the design phase intensively. The results of the dynamic process simulation have been used to optimize the process control strategy and fail-safe operation.

3.1. APROS Flow Models

There are three different thermal hydraulic solution models available.[13] For single phase flows, whether liquid or gaseous, the application of the three-equation model is recommended. In the presented case, the three-equation model is applied for the hot off-gas. If two phases occur in the simulated fluid, the three-equation model solves the conservation equations for a mixed phase. Therefore, models simulated with the three-equation system are calculated very quickly. Due to unpredictable

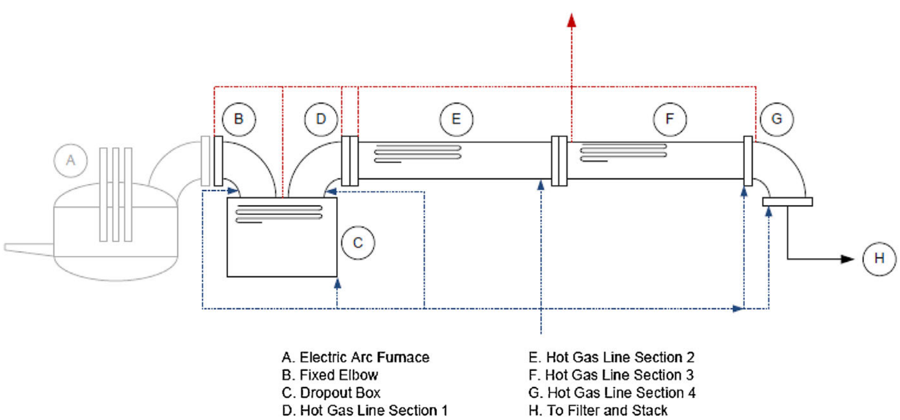

Figure 4. Process diagram of the modeled water cooled hot gas line for heat recovery.

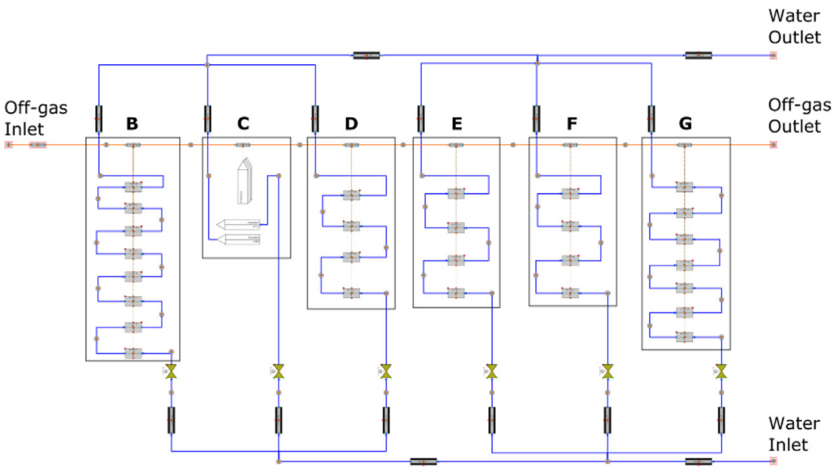

Figure 5. APROS process diagram of the simulated water cooled hot gas line with sections B–G.

temperature gradients on the water side and the uncertainty about unwanted evaporation, the six-equation model is applied for the water side. The six-equation model delivers more accurate results, because of the separated calculation of the conservation equations for the liquid and the gaseous phase.

The solution system accounts accumulation phenomena and therefore changes of mass, momentum and energy and is based on one-dimensional conservation equations for mass (Equation 1), momentum (Equation (2)), and energy (Equation 3) in the form of

$$\frac{\partial(\alpha\rho)}{\partial t} + \frac{\partial(\alpha\rho u)}{\partial z} = s_1 \tag{1}$$

$$\frac{\partial(\alpha\rho u)}{\partial t} + \frac{\partial(\alpha\rho u^2)}{\partial z} + \alpha\frac{\partial p}{\partial z} = s_2 \tag{2}$$

$$\frac{\partial(\alpha\rho h)}{\partial t} + \frac{\partial(\alpha\rho u h)}{\partial z} = s_3 \tag{3}$$

The balances (1), (2), and (3) are discretized by the pipe length z with a constant cross-sectional area a. The flow velocity of the simulated fluid is represented by u and the enthalpy by h and includes the kinetic energy $w^2/2$. The terms on the right-hand side of the equations represent source terms, whereby S_1 stands for mass source, S_2 for momentum source, and S_3 for heat source within the control volume.

The numerical solution algorithm is based on the principles presented from Siikonen.[14] With the application of a fully implicit solution procedure the conservation equations for energy, mass, and momentum for both phases are solved. For the convection terms upwind values are used and for the discretization in space a staggered mesh is applied. The resulting set of non-linear equations is solved iteratively in the same manner as in SIMPLE method for a single-phase flow.[15,16] The values for pressure, density, and enthalpy are calculated in the center of the mesh cell and the flow related state variables like velocities are calculated at the cell borders. Inside the mesh cell, an average over the quantities of the whole cell is built. The state variables of the liquid and the gaseous phase are calculated as a function of pressure and enthalpy. The constitutive equations for heat transfer and friction are used to couple conservation equations for energy, mass and momentum. Detailed information of the high number of implemented empirical correlations for the constitutive equations for friction and heat transfer used in APROS can be found in the Functional Description.[13]

3.2. Model Description of the Heat Recovery Hot Gas Line

The model of the heat recovery hot gas line is based on membrane wall heat exchangers which are representing each section of the cooling pass. The water side components of the membrane wall heat exchangers are connected to the gas side components. The thermodynamic data of the gas side as well as of the water side are combined for calculation of the heat transfer coefficients and subsequently for the calculation of the transferred heat from the off-gas to the cooling water. The components of the model in Figure 5 are named similarly to the process diagram in Figure 4. On account of the expected high temperatures of the gas as well as the particle radiation in the first section of the hot gas line, the membrane wall of the fixed elbow (B) absorbs the biggest amount of the thermal energy compared to the following components of the cooling pass. To prevent overheating and unexpected evaporation inside the heat exchangers of the hot gas line, a proper cooling water mass flow has to be ensured.

The drop out box (C) is modeled with wall side heat exchangers characterizing the water cooled roof of the drop out box. The following sections (D, E, F, and G) are modeled with meandering heat exchangers, similar to the fixed elbow, with different section lengths wherein the water is guided in meandering fashion. Due to the lack of accurate enough gas and particle radiation correlations for high dust loads on the gas side of the heat exchanger modules, the heat transfer of each section has been modified. The load cases for the steady state model validation can be taken from **Figure 6**, whereas the off-gas volume flow and the temperature are normalized to the design case of the thermal calculations. The graphs for the temperature and the volume flow are characteristically for the investigated EAF and describe charging, melting and refining phase of the process. Based on the results of the conducted steady state model validation with the power plant simulation and calculation software PPSD (former known as KED) the radiation constant k_{rad} in Equation **(4)** as well as the convection constant k_{conv} in Equation **(5)** have been varied. Equation 4 and 5 are showing the heat transfer coefficient calculation implemented in APROS with the heat transfer coefficient for radiation α_{rad} and convection α_{conv}, the Stefan–Boltzmann constant SB, the wall temperature T_w and the fluid temperature T_i as well as the mass flow on the gas side.

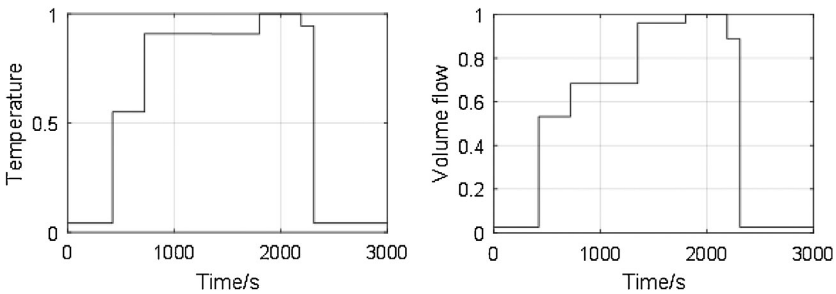

Figure 6. Load cases for the steady state model validation.

$$a_{rad} = k_{rad} \cdot SB \cdot \frac{T_i^4 - T_w^4}{T_i - T_w} \quad (4)$$

$$a_{conv} = k_{conv} \cdot \dot{m}_{gas}^{0.6} \quad (5)$$

The value for the two constants with the minimum deviation of three part load cases and the design case has been implemented in the heat exchanger modules in APROS. Additionally, a fine adjustment has been performed with the efficiency of heat transfer. Efficiencies lower than 100% are typically for, for example, fouling and values greater than 100% mean the heat transfer calculated with the heat transfer correlations becomes more efficient. The gas side of the heat exchanger modules are modeled with the three-equation model. Having regard to the possibility of unintentional evaporation inside the hot gas line, the water side has to be modeled with the highest level of detail, that is, the six equation model is applied. The inputs, off-gas temperature and off-gas mass flow, are extracted from the process control system of the electric arc furnace and prepared for APROS as text file. APROS reads the inputs from the file and transfers it to the selected components as boundary conditions. It should be mentioned, that the modeling process is described for the fixed elbow only, representatively for all other sections of the hot gas line.

4. Results and Discussion

The hot gas line has been designed with theoretical transient graphs for off-gas temperature and off-gas mass flow. For the steady state model validation the design case and three part load cases, according to **Table 1** with different off-gas temperatures and volume flows, have been used. The design case of the heat recovery concept is therefore described by the maximum temperature and volume flow of the off-gas. The error is calculated as the difference between the APROS and the PPSD simulation results referred to the PPSD results in the form

$$APROS\ Error = \frac{PPSD\ Results - APROS\ Results}{PPSD\ Results} \quad (6)$$

The steady state model validation showed a quantitative match with a maximum error of 2% of the transferred heat at higher load cases as it can be taken from **Figure 7**. High load cases are represented by load case 3, 4, and 5. Load case 1, which occur less than 40% of the electric arc furnace tap to tap time, shows the highest error. Subsequently, it can be claimed that the model of the heat recovery hot gas line simulates the steady state cases very accurate and reliable especially at higher loads.

For control strategy optimization and the simulation of startup procedures steady states are not sufficient. Therefore, the dynamic behavior of the tubes and the time delay at long distances has to be considered and calculated. Measured values from the commissioning process for off-gas temperature and mass flow have been applied as boundary conditions in APROS for the transient model validation. **Figure 8** shows the comparison of the simulated and the measured cooling water volume flow in the fixed elbow. The simulated results agree very well with the experimental data not only in a qualitative manner but also in a quantitative manner. The good correlation of the volume flow confirms a well optimized control strategy of the circulation pumps. The relative error between the experimental data and the simulation results are not greater than 2.3%. Depending on the load case of the furnace the cooling water volume flow is increased or decreased. During the melting process, while the off-gas mass flow and subsequently the emitted thermal energy is high, the mass flow of cooling water is increased according to the implemented control strategy of the temperature control system. The melting process can be observed between 500 and 2000 s in Figure 8. During EAF idle times, while charging the furnace with scrap (0–200 s) or during tapping liquid steel (2500–3000 s), the volume flow is decreased. The reduction of the cooling water volume flow reduces thermal losses to the environment of the heat recovery hot gas line, as the heat transfer coefficients are lower and subsequently the heat transfer is decreased. Furthermore, the reduction reduces the electrical power for pumps during idle times. However, the cooling water flow cannot be reduced significantly, since low water velocities in the tubes would induce thermal stress in the membrane wall.

Table 1. Results of the steady state model validation with PPSD

	Standardized EAF load cases		Cooling water outlet temperature	Heat transferred
Load case	Off-gas volume flow	Off-gas inlet temperature	APROS error	APROS error
1	0.53204	0.55146	0.31%	5.42%
2	0.96193	0.90924	0.46%	2.05%
3	0.88832	0.94505	0.26%	1.38%
4	1	1	0.14%	1.46%

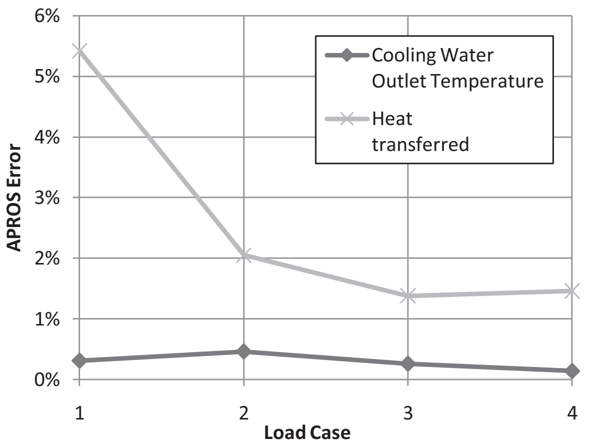

Figure 7. APROS error, compared to the PPSD simulation results.

In **Figure 9** the simulated values and the experimental data for the hot gas line inlet and the outlet temperatures are compared. Additionally, the off-gas temperature is plotted in the diagram for electric arc furnace operation identification. Similar to the volume flow, the simulated temperatures agree in good manner with the measurements. The maximum relative error is approximately 5%. In consequence of the reduced mass flow, the temperature increases from the beginning of the simulation until 600 s simulation time to the temperature set point of 190 °C, rather quickly. Subsequently, the control systems for the cooling water mass flow and the cooling water inlet temperature are working in harness for reaching the outlet temperature set point as quickly as possible. To prevent emergency stops of the furnace due to exceeding of the maximum allowed temperature in the hot gas line, the control parameters have to be adjusted in respect of minimum overriding but with a quick response to temperature changes. If the overriding of the temperature would be too high, evaporation with a subsequent enormous pressure jump could occur in the hot gas line. The pressure jump would be harmful for all the components of the heat recovery system. Moreover, smooth thermocline storage operation without disturbance of the temperature layers can be achieved with a small gap around the set point. Disturbances of the temperature layers will lead to thermal losses due to mixing of the hot and the cold layers of the water inside the storage tank. High temperature peaks in the cooling system would force an electric

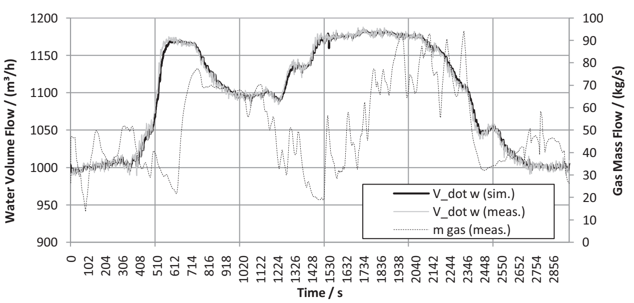

Figure 8. Comparison of the hot gas line cooling water volume flow measurements and simulation data.

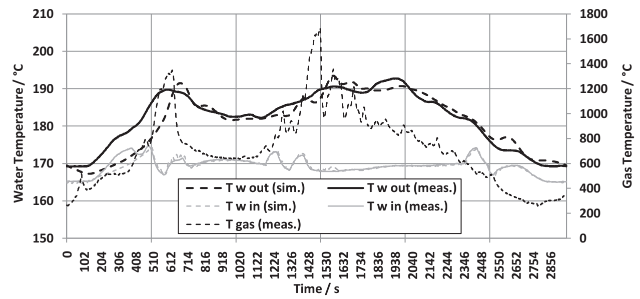

Figure 9. Comparison of the hot gas line cooling water temperature measurements and simulation data.

arc furnace emergency shut down and entails production risks of the furnace. Hence, small bands around set points are highly recommended and guarantee production reliability. The combination of an intelligent control system and highly optimized control parameters ensures high thermal output in form of saturated steam and minimizes production risks for the steel plant.

Summarizing the findings of the comparison between the simulated data and the experimental data from the heat recovery plant, it can be claimed, that the model represents the real plant in an excellent manner. The developed model gives the opportunity for further optimization of the control strategy in terms of maximizing the recovered heat and smooth operation conditions. Moreover, the presented heat recovery approach gives steel plant operators a reliable and highly efficient possibility to use unrecovered sources of thermal energy which are usually dissipated to the environment.

5. Conclusion

The objective of the dynamic process simulation was to demonstrate the behavior of the transients of this dynamic and fluctuating process and subsequently the validation of the developed process model with measurements. Due to the novelty of this heat recovery plant there are no experiences of existing plants available for the thermal design process. The design process has been supported successfully with the investigations of the dynamic behavior within the commercial process simulation software APROS. The findings of the simulated hot gas cooling line have been implemented during a step by step optimization process. After hot commissioning of the waste heat recovery plant the simulation results and measurements have been compared. The received results and the measurements show a high level of accuracy. It can be claimed that the APROS model describes the dynamic behavior of the real heat recovery hot gas line with sufficient precision. Furthermore, the model represents a reliable tool for further investigations such as different EAF load cases and parameter studies for operation condition optimization.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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