Journal of Physics: Conference Series

OPEN ACCESS

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To cite this article: T Steinparzer *et al* 2012 *J. Phys.: Conf. Ser.* **395** 012158

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Heat exchangers and thermal energy storage concepts for the off-gas heat of steelmaking devices

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Abstract. The fluctuating thermal emissions of electric arc furnaces require energy storage systems to provide downstream consumers with a continuous amount of thermal energy or electricity. Heat recovery systems based on thermal energy storage are presented. A comparison of different thermal energy storage systems has been performed. For the purpose, suitable heat exchangers for the off-gas heat have been developed. Dynamic process simulations of the heat recovery plants were necessary to check the feasibility of the systems and consider the non-steady-state off-gas emissions of the steelmaking devices. The implementation of a pilot plant into an existing off-gas duct of an electric arc furnace was required to check the real behavior of the heat exchanger and determine suitable materials in view of corrosion issues. The pilot plant is presented in this paper.

1. Introduction

Steel production is one of the most important industrial high-temperature processes. There are mainly two alternative routes for steelmaking. The first is the converter route. Steel is produced by a converter – mainly a basic oxygen furnace (BOF) also called O_2 converter - using hot metal from blast furnace and recycled scrap. The second is the electric arc furnace (EAF) route. The electric arc furnace is the steelmaking device of a mini mill. Scrap steel and partially hot metal are melted in the electric arc furnace to produce crude steel. The production routes are shown in Fig. 1. Steel production is a combination of batch processes. Thus the discontinuous steelmaking process leads to a variable thermal energy output.

Increasing electric power costs make energy efficient steel production including waste heat recovery systems more attractive for mill operators. Energy related green house gas emissions are further the major part of emissions from the steelmaking process. Thus energy recovery systems are seen as key technology for an energy efficient steelmaking process (cf. [1]).

Target of this work is to recover waste heat of steelmaking processes. Therefore adequate heat exchangers and thermal energy storage systems were designed to ensure a continuous energy recovery. The off-gas heat exchanger was designed alternatively as a waste heat boiler or as a one phase heat exchanger for a heat transfer fluid. The discontinuous amount of energy from the off-gas transferred in the heat exchanger is buffered in a thermal energy storage system.

Detailed concepts for each thermal energy storage system have been developed. The concepts include the design of heat exchangers and storage systems. All storage systems have been simulated and modeled in a suitable process simulator.

Fig. 1: Overview of steelmaking routes, schematically [2].

2. Thermal Energy Storage Systems for the Waste Heat of Steel Production

Due to the fluctuating off-gas emissions of the steelmaking processes (electric arc furnace and basic oxygen furnace) thermal energy storage systems (TES) are necessary to provide downstream systems with a continuous amount of thermal and electric energy.

For an efficient waste heat recovery system the selection of suitable thermal energy storage media and systems is essential. Basically both sensible and latent heat storage systems are feasible. Thus a comparison of suitable thermal energy storage systems regarding the requirements of steelmaking devices has been done. The following media for sensible thermal energy storage were taken into account: thermal oils, molten salts, liquid metals, concrete and sand. For latent thermal energy storage systems water/steam and phase change materials were considered. These media have been adapted and combined in order to apply them for thermal energy storage within heat recovery systems for steelmaking devices.

2.1. Methodology

All thermal energy storage systems were designed by steady-state calculations for the maximum respectively minimum power emissions. Based on these design data the thermal energy systems have been modeled in a non-steady state process simulator.

2.1.1. *Modelling.* For the transient calculation of the thermal energy storage systems a dynamic process simulator called APROS (Advanced Process Simulator, developed by VTT Finland) or computational fluid dynamics (CFD) programs were used. Both calculation programs use a finite volume method for discretisation of the equations. The solution principle is based on the SIMPLE algorithm. The calculation of mass flow and temperatures is done by the mass and energy conservation laws. Since some thermal energy storage media were not implemented yet into the simulation tools, properties of existing materials had to be adapted. Momentum balance and storage of heat or mass inside the heat exchangers or tanks are considered. All tanks are ideally mixed vessels. The non-steady state conductive heat transfer is solved according to the following equation, where T is the temperature inside the wall, r the radius of the pipe and $\dot{Q}$ the transferred heat. The variables a and c_p are material properties.

$$\frac{dT}{dt} = \frac{d^2T}{dr^2} + \frac{1}{r} \cdot \frac{dT}{dr} + \frac{\dot{Q}}{a\dot{m}c_p}$$

2.2. Thermal Energy Storage Systems

For the following thermal energy storage systems respectively media, detailed calculations have been done.

- Latent thermal energy storage: Steam accumulators and phase change materials.
- Sensible thermal energy storage: Molten salts, concrete and sand.

Liquid metals as heat transfer fluid have been eliminated because of their high density and therefore their bad pump-ability. Thermal oils are problematic due to their fire load. An organic Rankine cycle leads only to good efficiencies at low off-gas temperatures.

The volumetric thermal energy storage capacity of different thermal energy storage systems (TES) is compared in Fig. 2. The figure shows that molten salts have the best characteristics for providing sensible heat. These systems were compared to each other according to different heat exchanger characteristics. ECO stands for economizer, EV for evaporator and SH for superheater. As evaporator pressure 80 bar and as superheating temperature 450°C have been selected.

Fig. 2: Volumetric storage capacities of the considered TES systems arranged according to different heat exchanger characteristics.

2.2.1. *RUTHS Steam Accumulators.* Steam accumulators are a proven technology for buffering of saturated steam. They are already applied for buffering the saturated steam from the cooling stack of a basic oxygen furnace. Due to the required high maximum pressure resulting from the sliding pressure operation thick-walled tanks are necessary.

2.2.2. Phase Change Materials. Phase change materials (PCM) are used for providing downstream systems with saturated steam. One possibility is to support the steam accumulator by using phase change materials. The support is feasible if the volumetric energy density of the PCM is higher than the energy density of the steam accumulator. Main challenges for PCM are the selection of suitable materials for corresponding steam pressure of the waste heat boiler and the heat transfer from the steam into the PCM. In this case PCM based on nitrate salt mixtures were chosen.

2.2.3. *Molten Salts.* Molten salts as heat transfer and storage media are already used for concentrating solar power plants. Molten salts can be used for storing the energy and as heat transfer fluid. Molten salts allow high fluid temperatures which in principle can lead to high cycle efficiency. Nevertheless gas side corrosion aspects need to be taken into account.

2.2.4. *High Temperature Concrete.* Another approach for storing sensible heat is the use of solids. High-temperature concrete is therefore an option. The heat transfer between heat transfer fluid and solid media is enhanced by a finned pipe. Main challenge for using concrete for thermal energy

storage is the creeping of concrete. This leads to gaps between the pipe and the concrete which declines heat conduction.

2.2.5. Fluidised Bed. Fluidised beds can be used for storing sensible heat. Main advantage of fluidised beds is the enhanced heat transfer between pipe and storage media, for example sand (cf. [4]). A disadvantage lies in parasitic losses for fluidisation.

3. Heat exchangers

To recover the off-gas heat of the steelmaking process suitable heat exchangers are required. The heat exchanger concepts depend on the heat transfer media. Gas side high temperature corrosion is a topic which needs to be considered independently from the primary fluid. This has been handled by a testing plant.

3.1. Waste Heat Boilers

At state of the art dedusting systems for steelmaking processes the off-gas duct is water-cooled. The off-gas heat is transferred to the environment. The new approach is to use the waste heat for energy production. A common solution is to replace the water-cooled off-gas duct by evaporation cooled systems.

For water/steam as primary fluid, the off-gas duct has to be designed as a waste heat boiler. The process flow diagram is given in Fig. 3. High gas velocities in the inlet duct and high dust loading are design challenges. These challenges have been handled by appropriate heat exchanger design.

Fig. 3: Process flow diagram for the waste heat boilers.

3.1.1. *Blast Oxygen Furnace.* For the BOF an adequate system for producing saturated steam is already state of the art. It is called cooling stack and shown in Fig. 4. The cooling stack mainly consists of a radiation pass with evaporation cooled membrane walls. The off-gas leaves the cooling stack with a temperature around 800°C.

3.1.2. Electric Arc Furnace. For electric arc furnaces nothing comparable has been built. Thus an efficient waste heat boiler was designed for the electric arc furnace. The design of the waste heat boiler is shown in Fig. 5. The waste heat boiler is designed as five pass system including radiation passes, evaporation panels, evaporation bundles and an economizer for preheating the feed-water. Using the presented design the off-gas can be cooled down to 200°C.

Fig. 4: Design of the cooling stack for basic oxygen furnaces.

3.1.3. Modelling and Simulation Results. Both steam generators were modelled and simulated in APROS. The modelling of the heat exchangers lead to the following equations for mass and energy balance. A represents the cross-section of the pipe and w the inlet or outlet velocity of the fluid. L is the length of the pipe and ρ the density of the fluid. p stands for the pressure and h for the enthalpy of the fluid. $\dot{Q}$ is the transferred heat.

$$\mathrm{A} \cdot \frac{\mathrm{d}}{\mathrm{dt}} \int_0^{\mathrm{L}} \rho(\mathrm{l}) \cdot \mathrm{dl} = (\rho \mathrm{w}_{\mathrm{in}} - \rho \mathrm{w}_{\mathrm{out}}) \cdot \mathrm{A}$$

$$A \cdot \frac{d}{dt} \int_0^{L} [\rho(l)h - p] \cdot dl = [(h\rho w)_{in} - (h\rho w)_{out}] \cdot A + \dot{Q}$$

Equations for convective and radiative heat transfer were adapted to fit the appropriate equations in [5]. The simulation showed that the steam generator design is capable to support the dynamic behavior of the furnaces. Fig. 6 shows the combustion temperatures and further off-gas temperatures in the waste heat boilers. The peak in the first meters of both curves result from oxidation reactions with leakage air.

Fig. 5: Design of the waste heat boiler for electric arc furnaces.

Fig. 6: Off-gas temperatures in the heat exchangers plotted versus heat exchanger length.

3.2. Molten Salt Off-Gas Heat Exchanger

For molten salt as primary fluid, the heat recovery system needs to be designed for fast draining of the liquid and for freezing prevention. The process flow diagram is shown in Fig. 7.

Fig. 7: Process flow diagram of the molten salt off-gas heat exchanger.

Using molten salt as heat transfer and storage media makes a special designed off-gas molten salt heat exchanger essential. The heat exchanger was designed as self-draining if the pumps stop. Thus up-down constructions for the tubing were chosen. The design of the heat exchanger is printed in Fig. 8.

Fig. 8: Design of the off-gas molten salt heat exchanger.

3.2.1. Modelling and Simulation Results. The molten salt off-gas heat exchanger has been modelled and simulated in APROS. For the first set of calculations possible limitations through gas side corrosion were not considered.

The search for high efficiency of the process leads to high fluid temperatures, high tube wall temperatures and hence the requirement to find an optimum between acceptable stress and minimum primary fluid mass flow. The flow arrangement in the radiation part of the heat exchanger therefore needs to ensure sufficient fluid velocities while minimizing overall mass flow. The necessary circulation mass flow density in the radiation part was fixed due to the thermal stress inside the membrane wall. Fig. 9 shows the thermal stress inside the membrane wall depending on the molten salt velocity and temperature. The figure illustrates that the selection of the necessary mass flow inside the pipes depends on the permissible stress inside the membrane wall.

Fig. 9: Thermal stress inside the membrane walls of the heat exchanger.

3.2.2. *Pilot Plant.* To validate the heat exchanger design a pilot plant based on molten salt as heat transfer fluid has been installed into the off-gas duct of an operating EAF. One of the major goals is to investigate material properties of several heat exchanger grades in respect to high temperature chlorine corrosion as well as the impact of EAF dust and off-gas composition on wear and heat transfer. The tests will be performed during one year. The test rig consists basically of a molten salt storage tank, a molten salt off-gas heat exchanger, a molten salt air cooler and various control and measurement instruments. A drawing of the pilot plant is presented in Fig. 10. The plant is designed to ensure drain-ability of the molten salt. Heat exchanger wall temperatures up to 450°C shall be investigated.

Fig. 10: Drawing of the pilot plant.

Commissioning has started in April 2012. First experimental results will be available in July 2012. The testing plant has been modelled and simulated in APROS to validate the simulations.

4. Discussion

4.1. Comparison of the Thermal Energy Storage Systems

A comparison of the thermal energy storage systems has been made based on the simulation results. Main features were heat capacity, storage size, storage costs and dynamic behavior regarding steelmaking.

The comparison showed that sensible thermal energy storage systems are well suited for accumulating the waste heat. Molten salts and fluidized beds show a better dynamic capability than high-temperature concrete. The challenge for the TES system is the heat transfer into the storage media. Due to this fact molten salts and fluidized beds are preferred for thermal energy storage. The storage efficiency depends on the storage media properties and on thermal losses, which decrease with the size of the system. Most sensible thermal energy storage systems are the result of recent investigations and therefore are not yet economically optimized. One possible way to deal with this issue is to combine proven and new technologies. Regarding latent thermal energy storage RUTHS steam accumulators seem in the short term more feasible than PCM due to their capability to support the dynamic behavior of the furnace.

4.2. Comparison of the Steam Generator Designs

Waste heat boilers are widely applied in industrial applications. The waste heat boiler designs for the application in BOF and EAF are custom designed to handle the process dynamics. Higher boiler pressure leads to higher efficiency but also higher costs. To provide downstream systems with constant steam mass flow additional thermal energy storage systems are required. Thus a heat transfer medium cycle and a storage medium cycle are necessary.

Molten salts are a pressure-less alternative. The molten salt heat exchanger leads to only one thermal energy storage system. Nevertheless the risk of freezing is a design challenge.

For the near future waste heat boilers are easier to apply. Molten salts are a simple alternative for the future with advantages due to the low pressure also in respect to operation safety.

4.3. Summary and Future Work

Concepts for the off-gas heat recovery of steelmaking devices have been developed. Waste heat boilers and steam accumulators can be considered a proven technology but they need to be properly designed for the dynamic process conditions at steelmaking. The heat recovery systems based on molten salt could be a future solution due to the simple overall concept. To check the economic benefit of molten salt systems equipment costs have to be evaluated and compared to a water/steam system.

The results of the material tests from the testing plant will determine the tolerable respectively economic temperature limits regarding materials. The results can be used for both heat exchanger systems (based on water/steam or molten salt).

Acknowledgements

The presented work has been financially supported by the Austrian research promotion agency (FFG – project number 832000).

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