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Possibilities for the Reduction of Water Consumption in Steel Industry and Continuous Steel Casting: An Overview

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Recent environmental regulations have resulted in an increased effort for retrofits of industrial facilities. Besides energy and emissions, the minimisation of the water consumption is one of main goals as water is becoming more and more limited. Steel industry represents a chain of industrial processes, in which a vast amount of water is consumed and degraded. The paper concerns with possibilities for the reduction of the water consumption in the steel industry. The analysis is performed from two points of view: an overall insight into involved processes, and an identification of technical ways applicable for the minimisation of the water consumption in continuous steel casting. Results indicate that though coking and ironmaking are the most water-demanding tasks, there are also ways for minimisation of the water use in the casting process. Optimal arrangement and design of cooling nozzles allow for 10–20 % reduction, while the use of nanofluids in spray cooling seems to be a more effective way allowing for about 70 % reduction of the water consumption.

1. Introduction

During the last two decades, a significant effort has originated with the aim to reduce negative impacts of industrial facilities to the natural environment. The focus has particularly been concentrated on minimisation of production of emissions such as CO_2, SO_2, and NO_x, and the sustainable utilisation of natural resources, especially water. The steel industry represents a source of a vast amount of emissions as well as solid particles and dust, which are emitted to the atmosphere (Zhou and Yang, 2016). It was reported that the steel industry recently re-invests about 13 % of the annual revenue into capital investment projects and process improvements (World Steel Association, 2018). The chain of processes in the steel industry is fairly demanding as it involves a massive consumption of energy (He and Wang, 2017) and water (Gao et al., 2019). The trend of steel production is still increasing, currently by about 2 %/y as demonstrated in Figure 1a. The reason for high energy and water consumption in the steel industry is rather apparent: a large amount of electricity or fuels such as coal is transformed into heat in order to process the iron ore and/or to melt the scrap steel into the melt. More than 95 % of the total world steel production is cast by means of the continuous steel casting method (Thomas, 2018). In continuous steel casting, heat is withdrawn from the melt allowing for its solidification, and water or air-mist spray nozzles are widely utilized for spray cooling and heat removal.

In order to quantify demands of energy and water in the steel production, consider the production of 1 t of steel from the scrap. In such case, about 1.25 GJ/t of heat (assuming the enthalpy difference of 1,250 kJ/kg in the temperature range between 1,600 °C and the room temperature) is required to melt the scrap from the room temperature to the melting point of steel, which is about 1,550 °C. That corresponds to about 365 kWh/t of electricity converted to heat with 95 % efficiency. It is worth pointing out that the mentioned estimation of heat consumption considers only melting of the scrap. The overall average energy consumption taking into account all the processes in the steel production was reported of about 20.3 GJ/t (World Steel Association, 2018). As for the solidification and cooling during the casting process, the liquid steel – the melt – is solidified and cooled down to about 800 °C by means of a water cooling system, which represents about 750 MJ/t of withdrawn heat

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(cooling from 800 °C to the room temperature takes place by air-induced natural convection and radiation without the use of water). About 60 % of this amount of heat is withdrawn by means of cooling nozzles, which use water in a once-through manner. In other words, approximately 450 MJ/t of heat withdrawn from the cast strand need to be used to warm and evaporate water impinging to the steel surface during the casting process. Water requires about 2.6 MJ/kg of heat for raising its temperature from 10 °C to the boiling point at barometric pressure and its complete evaporation. This means that at least about 175 L of water is required just for cooling of 1 t of steel being produced. Again, note that this amount of water is for spray cooling only. A much larger amount of water is in total needed for the production of 1 t of steel. Wang et al. (2017) reported that about 4 m^3 of fresh water is consumed per 1 tonne of crude steel produced.

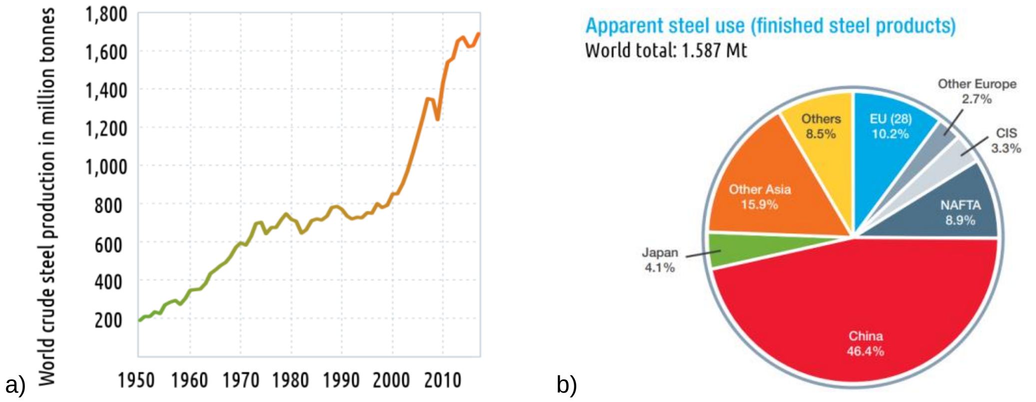

Figure 1: a) The world trend of total crude steel production, b) apparent steel production (in finished products) in 2017. Adapted from (World Steel Association, 2018)

Considering the recent world steel production demonstrated in Figure 1, about 1,600 Mt of steel (in the form of finished products) was produced in 2017 (World Steel Association, 2018). That implies that about 280 Mm^3 of water was consumed in 2017 for cooling in continuous steel casting. As can be seen in Figure 1b, China is the dominant producer of steel with a share of almost 50 % of the total world steel production. The comparison of shares in time indicates that China has increased its steel production by about 12 % in the last ten years (World Steel Association, 2018), and the increasing trend of steel production for China is expected to continue in the future. Therefore, especially China should pay great attention to water sources, sustainable use of water, its balance in the natural environment, but also to emissions and other issues. Detailed analyses can be found elsewhere, e.g. in An et al. (2018) who analysed possibilities for the reduction of energy and CO_2 emissions in the steel industry in China. The authors reported that there is a great potential for the minimisation of the production of CO_2 emissions of about 800 $MtCO_2$ during 2015–2030.

As can be deduced from the mentioned large numbers, any technological improvement in the cooling technology leading to a reduced consumption of water, even in the order of 0.1 %, has a potential to globally spare a vast amount of water in the natural environment and minimise the water footprint. It is important to seek for ways and technologies, which would allow for the minimisation of the water consumption in the steel industry. The present paper aims at the identification of currently available solutions for the reduction of the water consumption in the steel industry. Insights at the level of processes as well as at the level of continuous steel casting technology have been made. Presented solutions have been analysed, and their potential and impact to the minimisation of the water consumption were discussed.

2. Ways for the reduction of the water consumption in the steel industry

From the point of view considered in the present paper and focused to the reduction of the water consumption in the steel industry, two categories of studies have been published in recent years. One category of papers is concerned with the overall assessment and general analysis of processes involved in the steel industry, while another category of studies consists of papers, which are focused to particular technical solutions aimed at the improvement of the cooling process. Such improvement of cooling indirectly enables the reduction of the water consumption. Papers from both the categories are discussed separately in the following sections.

2.1 Overall analyses of the water consumption in the steel industry

In the recent literature, there are a number of studies aimed at the overall assessment of the entire chain of all processes, which are involved in the transformation of the iron ore (or the steel scrap) into finished products.

Such analyses allow for the identification and quantification of processes, which are responsible for the huge consumption of water. The process optimisation and/or possibilities for the reduction of the water consumption at the level of processes are often discussed. However, the overall view of these studies is rather broad, and such studies do not consider details and specific ways for the reduction of the water consumption.
As explained above, the water consumption in industrial processes (~$1.2 \cdot 10^{11}$ m^3 in 2017) is especially important issue in China (NBSC, 2018). Wang et al. (2017) presented an analysis of the water-energy-emission nexus (WEEN) in the steel industry and at steel plants in China. The material and energy flow analysis was applied to identify the flows of water, energy, and emission in five main processes (coking, sintering, iron making, steel making, and rolling) involved in the steel industry. The authors reported that in 2015, based on the industrial-level WEEN model for a Chinese steel plant, about 6 m^3 of water and 300 kWh of electricity were used in relation to the WEEN for the production of 1 t of crude steel, which corresponds to about 66 % of the total water consumption and 7 % of the electricity consumption in the steel production, respectively. As for the water consumption, the analysis revealed that about 71 % of water was used for cooling, while the rest for the pollutant removal. The authors used a Pareto optimisation model for the determination of scenarios, which minimise the production of emission. Gao et al. (2017) carried out an analysis of the water consumption in the steel industry. The concept of the water carrier and water quality was introduced. The use of the water quality indicator allowed for the conversion of the use of water with different qualities into an equivalent amount of fresh water. The authors applied their model to a steel plant in China, and they reported that the equivalent fresh water consumption was about 130 m^3/t, while traditional methods considering only the water volume (quantity) without its quality resulted in about 195 m^3/t of final steel products. Figure 2 shows the detailed results presented by Gao et al. (2017) for the case a) considering the water quantity and b) considering the water quality.

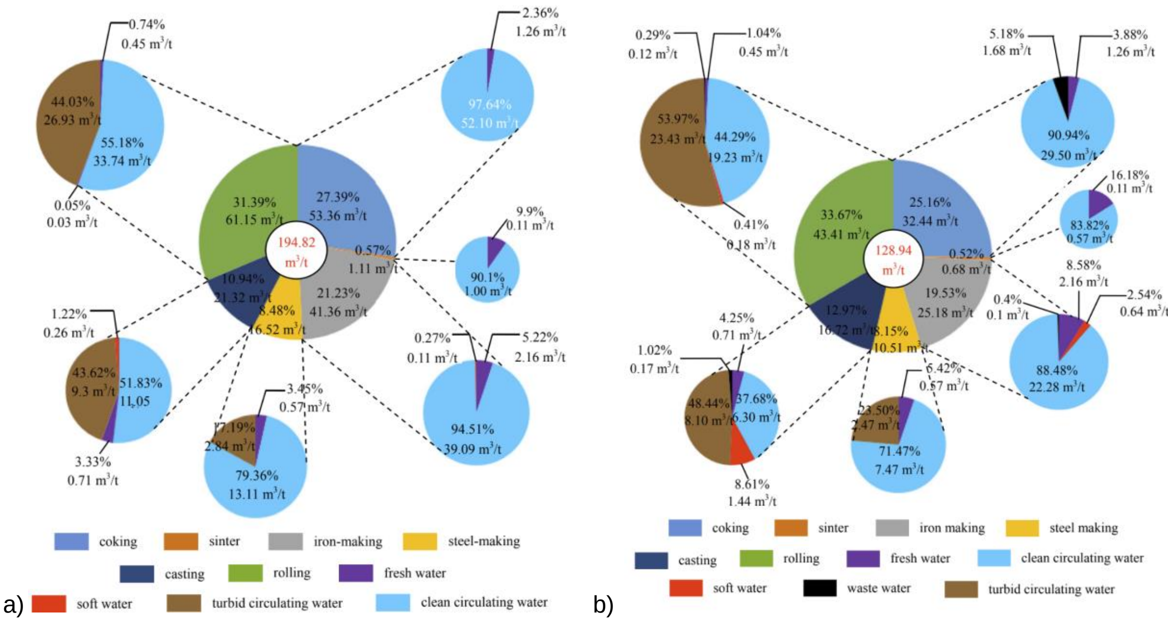

Figure 2: Water consumption in the production chain of steel industry: a) considering water quantity only, b) considering water quality using water quality analysis. Adapted from Gao et al. (2017)

The present paper considers possibilities for the reduction of the water consumption in continuous steel casting and Figure 2 demonstrates that when the water quality is considered, about 17 m^3 of water of all quality levels are used in the casting process. As for spray cooling in the secondary cooling zone, the fresh water is usually used for this purpose due to higher requirements to the water purity preventing nozzle clogging and reducing the maintenance of the spraying system. Figure 2 shows that about 0.7 m^3/t of fresh water is consumed in the casting process, from which a part could be spared by approaches discussed later.
Gu et al. (2016) thoroughly reviewed and investigated the nexus between water savings and energy conservation in China taking into consideration the 12th Five-Year Plan, which was aimed, among others, at water management targets. They emphasised that water and energy are interconnected and complementary, but water policy makers often do not take into account the energy consumption. The authors introduced an energy-water evaluation methodology employing an input-output model. Relationship coefficients for the description of energy-water nexus were defined and evaluated; such coefficients can be utilised for the

identification of water savings. Wang et al. (2017) presented a study into the assessment of water-energy nexus in the steel industry. The authors developed a hybrid model for the estimation of overall water impacts of energy conservation measures, and the steel and iron industry in China was considered as the case study. It has been reported that a significant reduction of the water consumption could be achieved by the replacement and retrofit of blast oxygen furnace with an electric arc furnace, which would allow for about 10–16 % of water savings. Ma et al. (2018) carried out a life cycle water footprint analysis, which took into consideration grey and blue water. The study has been performed as a case study in China and in accordance with the methodology prescribed in the ISO 14046 standard. The life cycle assessment and water footprint analysis showed that the grey water footprint is higher than in the case of blue water. The authors reported that the optimisation of indirect processes in the steel industry (including ore mining and the magnesium oxide production) is a crucial task allowing for the reduction of the water consumption. Zhang et al. (2018) reported on the multi-scale water network optimisation in the steel industry, which took into account an intra-plant and inter-plant integration. The authors created a mixed integer non-linear optimisation model based on techniques of mathematical programming. The minimised objective function related to the total annual cost was used for the investigation of potentials for the reduction of the water consumption and for the optimisation of the water network. The authors investigated two study cases: with an indirect integration only, and with both the direct and indirect integration. They reported that the case with the indirect integration allowed for about 22 % reduction of the fresh water consumption, while in case of the direct and indirect integration the water consumption remained unchanged. Gao et al. (2011) analysed the use of water in the steel industry considering its quality. A model was built, and a substance flow analysis was used for the definition of the evaluation index system. The authors presented a study comparing the current and optimised state for a steel plant in China, and they concluded that the optimisation procedure allowed for the reduction of the fresh water consumption by about 11 %, and the waste water discharge was reduced by about 95 %.

2.2 Identification of ways for the reduction of the water consumption in continuous steel casting

In this section, specific technical solutions for the reduction of the water consumption in continuous steel casting are identified and analysed. The focus is concentrated to water spray cooling in the secondary cooling zone since spray cooling by means of cooling nozzles operates in an open once-through loop and accounts for about 60 % of the heat withdrawal during the casting process. There are two main approaches allowing for the reduction of the water consumption in spray cooling: a) development, improvement, and proper arrangement/optimal design of spray nozzles, and b) additives mixed with water at the inlet of the spray cooling zone. The underlying principle of these technical solutions is the increase of the heat transfer coefficient (HTC) and heat transfer efficiency of the spray. This means that with a more efficient technology the water flow fed to nozzles can be reduced providing a similar cooling power.

Wendelstorf et al. (2008) investigated heat transfer in spray cooling at high surface temperatures and in a wide range of water mass flow rates, which are applicable for spray cooling in continuous steel casting. They performed a set of measurements, and the focus was primarily put to the dependence of the HTC on the surface temperature and the water mass flow rate. Based on experimentally gained data, the authors proposed a correlation formula for the HTC as a function of the surface temperature and the water mass flow rate. The correlation was compared with data from other published studies, and a good agreement was reported. Figure 3a shows the developed correlation between the HTC and the water mass flow rate for the surface temperature of about 700 °C. As the red line in Figure 3a indicates, in the range of about 3–12 kg/m^{2}s of the water mass flow rate, the HTC can be approximated as a linear function. However, above 12 kg/m^{2}s of the water mass flow rate the HTC is not further linearly proportional to the water mass flow rate, and the intensity of heat transfer vs. the mass flow rate starts to decay. Similar results had also been observed by other investigators, e.g. (Pyszko et al., 2013). From the point of view considering the reduction of the water consumption, the increase of the mass flow rate above 12 kg/m^{2}s is not efficient, and it would be more effective to redesign the cooling section: the replacement of nozzles for large mass flow rates with a higher number of nozzles for smaller water mass flow rates, which are more effective in terms of the ratio between the cooling capacity (HTC) and the water consumption. Wang et al. (2013) developed a computer heat transfer model for continuous steel casting, which was validated using experimental measurements. The authors built an optimisation model, which utilised their heat transfer model as a temperature sensor. Optimisation was aimed at the determination of optimal water flow rates through cooling nozzles reducing the water consumption but keeping the surface temperatures at desired target ranges. Figure 3b shows the comparison of the water consumption in individual spray cooling zones before and after optimisation. As can be seen from Figure 3b, the optimisation procedure allowed for about 10–20 % reduction of the water consumption in spray cooling.

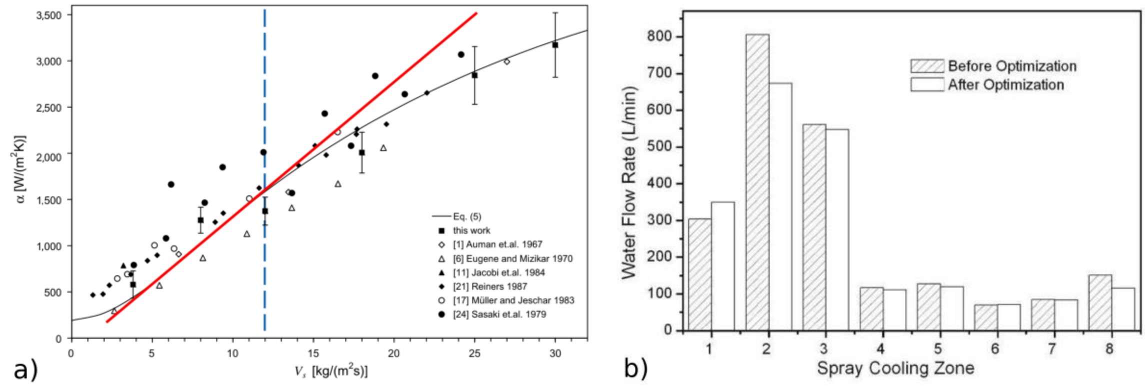

Figure 3: a) Correlation between the HTC (α) and the water flow rate (V_s) for the surface temperature of about 700 °C. Adapted from Wendelstorf et al. (2008); b) Water flow rates in the secondary cooling zone before and after the optimisation process aimed at the reduction of water consumption. Adopted from Wang et al. (2013)

Besides the optimal arrangement and design of cooling nozzles, another way for the increase of the HTC is the use of additives mixed with water. These techniques were intensively investigated in relation to nanofluids: water mixed with nanoparticles. Nayak et al. (2016) reported an experimental study into the enhancement of the HTC using nanofluids with applications for cooling of hot surfaces. Two nanofluids water-Al_2O_3 and water-TiO_2 were investigated in the concentration range between 0.01 % and 0.07 %. The authors reported that the addition of nanoparticles caused the increase of the HTC up to a certain concentration, and higher concentrations led to the consequent decrease of the HTC. The authors reported that the water-Al_2O_3 nanofluid performed better than the water-TiO_2 nanofluid, and in a specific configuration, the water-Al_2O_3 nanofluid almost doubled the HTC for pure water. Ravikumar et al. (2015) investigated the use of water-Al_2O_3 nanofluid with and without surfactants, and they reported in agreement with Nayak et al. (2016) that the cooling rate was significantly enhanced with nanofluids by up to 33 %. Ganvir et al. (2017) reviewed heat transfer characteristics of nanofluids in terms of heat transfer fluids. The authors reported that nanoparticles allowed for a significant increase (up to 40 % in case of water-Al_2O_3 nanofluid) of the thermal conductivity when compared with pure water. As for the economic evaluation of nanofluids, the end-costumer cost of Al_2O_3 nanopowder is about 150-500 USD/kg depending on the purity and other parameters (US Nano, 2019). In case of the concentration 0.01 %, the cost would be 15-50 USD/m^3 of water for spray cooling, which is not negligible. A reduction of costs related to nanofluids would therefore make them economically more viable.

2.3 Quantification of ways for the reduction of the water consumption in continuous steel casting

The foregoing two sections reveal that both approaches – (1) the proper design of nozzles in the spray cooling section including the consideration of the correlation between the HTC and the water mass flow rate, as well as (2) the use of nanofluids have a potential for the reduction of the water consumption in spray cooling in continuous steel casting. As for the former approach (1), the collected results indicate that rather lower values of water savings can be attained – ranging between 10 % and 20 %. Based on data presented in the literature and mentioned in Section 2.2, the latter approach (2) using nanoparticles mixed with water indicates that a more significant reduction of the water consumption could be achieved. Assuming the validity of a frequently used correlation for spray nozzles presented originally by Nozaki et al. (1976), the relationship between the heat transfer coefficient HTC and the water flow rate density *W* generated by a water spray nozzle can be estimated as $HTC \sim W^{0.55}$. Then, if HTC is doubled with the use of a nanofluid and the heat transfer rate keeps unchanged, *W* (i.e. the water consumption) can be reduced by about 70 %.

3. Conclusions

Ways for the reduction of the water consumption in the steel industry and in the dominant steel production method – continuous steel casting – were identified and analysed. Two different levels of insight into the topic were considered. One approach was aimed at an overall review at the level of processes involved in the steel production chain, including the iron ore processing at the beginning to the rolling of final products at the very end. This point of view enables the identification of processes where the water consumption is significant, as well as it enables the identification of processes, which allow for the reduction of the water consumption. Such processes include particularly coking and ironmaking. Another view provided in the study was focused to the identification and assessment of specific solutions for the reduction of the water consumption in the selected steelmaking process – casting – which is dominantly performed with the use of continuous steel casting. Two approaches were discussed in a more detail: the optimal arrangement and design of spray cooling nozzles, and the use of nanoparticles mixed with water and used for spray cooling. Results indicate that the former approach allows for the reduction of the water consumption by about 10–20 %. Nanofluids seem to have a higher potential for the reduction of the water consumption as a very small concentration of nanoparticles can even double the heat transfer performance of spray cooling. In the quantitative expression, the doubled heat transfer coefficient can allow for about 70 % reduction of the water consumption. However, further technical, economic as well as environmental studies need to be performed for a throughout validation of this approach.

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