Application of hydrogen operated burners in the electric arc furnace

L. Schüttensack[a)], A. Reinicke[a)], T. Echterhof[a)]

a) RWTH Aachen University – Department for Industrial Furnaces and Heat Engineering
schuettensack@iob.rwth-aachen.de

ABSTRACT

The steel making industry has one of the highest carbon dioxide emissions worldwide. The recycling route with the electric arc furnace (EAF) as the central aggregate emits less carbon dioxide in comparison to the blast furnace. Still, the EAF offers high potential for a reduction of the carbon dioxide emissions. One possibility is the substitution of natural gas by hydrogen in the auxiliary burners of the EAF. This substitution is investigated and analysed using a dynamic EAF process model. The model is able to simulate the combustion of natural gas as well as hydrogen. The differences in the operating conditions and properties by the hydrogen operated burners can be analysed in the results of the EAF process model.

INTRODUCTION

The electric arc furnace (EAF) is the most used aggregate in the steelmaking industry for steel recycling and one of the most used aggregates for the primary steel production.[1] In comparison with other aggregates for steel making e.g. the blast furnace, the EAF is low in green house gas emissions.[2] The main energy source in the EAF is electric energy which results in lower direct emissions. Still the carbon footprint for a ton of steel is high and leaves room for improvements.

In addition, auxiliary burners are utilized in the operation of the EAF. These are used as a secondary energy input and applied to heat “cold spots” in the steel scrap. The burners are operated with natural gas and are therefore a source of carbon dioxide in the EAF operation. The substitution of natural gas by hydrogen eliminates the carbon dioxide emissions from the burners and is therefore a way to further reduce the green house gas emissions of the EAF. The combustion of hydrogen influences all processes in the EAF and thus the effect has to be analysed.

A dynamic EAF process model first developed by Logar et al.[3]-[7] and implemented and improved by Meier[8] and Hay[9]-[12] can be used to simulate the hydrogen combustion and the effects on the EAF operation. The dynamic EAF process model is able to simulate the complex processes inside the EAF.

In scope of the RFCS funded project “DevH2forEAF” the substitution of natural gas by hydrogen in the auxiliary burners of the EAF is investigated. The effects of the hydrogen combustion on the EAF operation are simulated using the EAF process model with the addition of the hydrogen combustion to the process model. For further investigation of the effects of the hydrogen combustion on the EAF process, a pilot scale burner is operated within a pilot scale EAF. Especially the effect on the melt and slag composition are analyzed. These findings will help with the adjustment and validation of the hydrogen combustion in the EAF process model.

MATERIALS AND METHODS

The EAF is a highly complex system with a lot of variety in the operation parameters such as the scrap composition. Furthermore, the extreme conditions within in the EAF hinder the direct measurement of important properties during operation, for instance the temperature of the steel melt. The usage of a model simulating the EAF process can overcome this problem and give an insight on the processes inside the EAF.

The dynamic EAF process model consists of eight zones, as shown in Figure 1. Each zone has a homogeneous composition and temperature. The changes in composition and temperature of each zone are modelled by application of a mass and energy balances. The electric arc as well as the refractory lined walls and water-cooled vessel are respectively considered as a heat source or sink. These heat sources and sinks do not have a separate mass and energy balance in the model. Heat is transferred between the zones via direct contact as well as radiation, in addition chemical reactions and phase changes are also considered in the model. With this the resulting change of composition and temperature in each zone can be calculated and is reflected in the mass and energy balance of the zone.

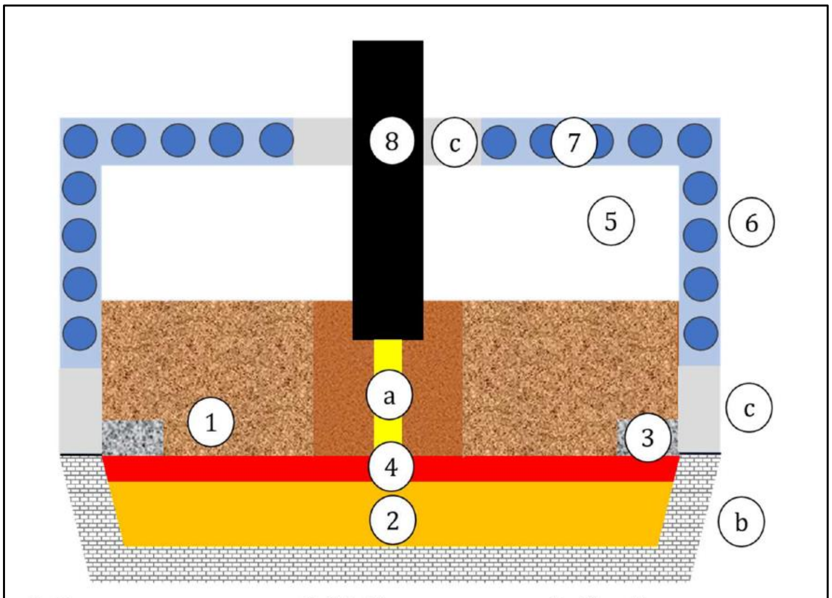


Fig. 1: Model zones (1-8) and heat sources/sinks (a-c) in the EAF process model [12]

For the estimation of the influence of hydrogen fired burners on the EAF process, the model is further expanded to simulate the hydrogen combustion. As part of the gas zone, the reactions of the burners installed in the EAF are considered. Since hydrogen is already present as a species in the gas phase, only the primary hydrogen combustion reaction is added to the model (Equation 1).

$$H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O \tag{1}$$

With the addition of this equation and the corresponding parameters and considerations/influences, it is possible to simulate burners operating with different fuel gas compositions. These fuel gas compositions can range from 100% natural gas to 100% hydrogen, including all mixtures in between. For a comparison of the operation of natural gas and hydrogen fired burners, parameters for the substitution of natural gas by hydrogen have to be determined. The caloric value of the burners has to be constant to generate the same energy input trough the burners independent of the fuel gas. Constants can be calculated to adjust the mass flow of natural gas and oxygen of the burner, which results in a mass flow of hydrogen and oxygen with the same caloric value. However, the results of the EAF process model for the combustion of hydrogen can not be validated yet. This validation will be carried out after the industrial trials with hydrogen burners.

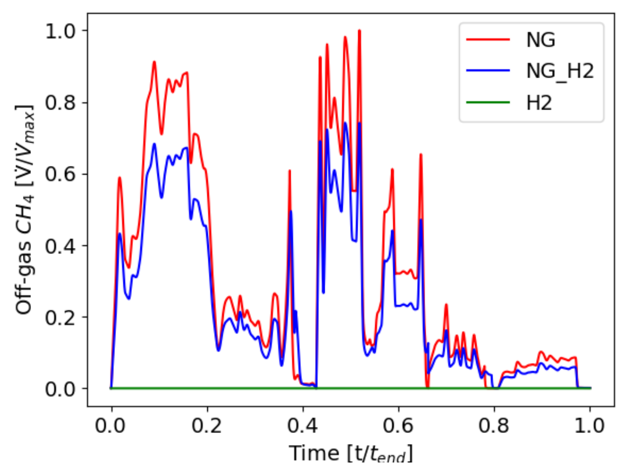
As a part of the RFCS funded project "DevH2forEAF" the substitution of natural gas by hydrogen in the auxiliary burners of the EAF is investigated. For further investigation of the effects of hydrogen combustion on the EAF process, a pilot scale burner is operated inside a pilot scale EAF. Especially the effect on the melt and slag composition are analysed. These findings will help with the adjustment and validation of the hydrogen combustion in the EAF process model. Before the installation of the pilot scale burner in the

EAF, free flame trials with fuel gas compositions ranging from 100% natural gas to 100% hydrogen were carried out to analyse the flame.

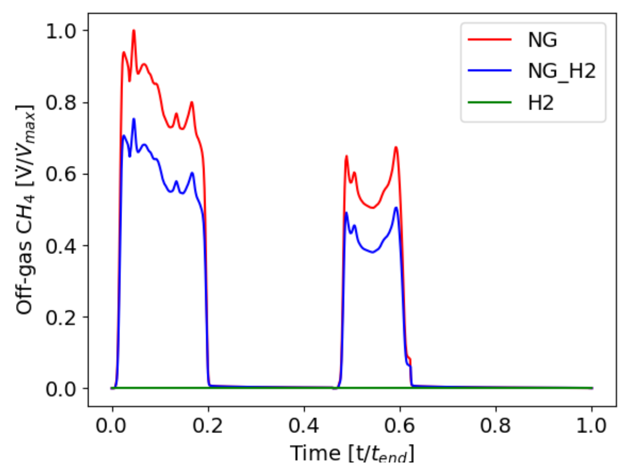
RESULTS AND DISCUSSION

In the following the results of different fuel gas compositions of the burners in the EAF process are shown. For a better comparison three different fuel gas compositions are analysed. The investigated compositions are as a reference 100% natural gas (NG), also a mixture of 50 vol-% natural gas and 50 vol-% hydrogen (NG_H2) and 100% hydrogen (H2). The axis of all shown graphs are normalised using the maximum of the investigated property. Furthermore, the process duration is also normalised. Each property is shown for two different EAFs. The two EAFs differ in their usage of burners. EAF 1 has more than double the amount of burner power than EAF 2. For this reason, the influence of the substitution of natural gas by hydrogen is more visible in the results from EAF 1.

In Figure 2 the normalised volume flow of non-combusted methane in the off-gas is shown for the different fuel gas compositions as well as the two different EAFs as they are simulated by the EAF process model. For a fuel gas composition of 100% hydrogen no methane is present in the off-gas, as it is not introduced by the natural gas through the burners. According to that for the mixture of natural gas and hydrogen less methane is in the off-gas than for 100% natural gas. Even though the graphs are normalised one can see that the burners are used more in EAF 1. In EAF 2 the burners are evidently only operated after a scrap basket is charged into the furnace, as a secondary heat source. In between the burners are completely turned off, as no methane is detected in the off-gas. In EAF 1 the burners are constantly operated with their power level adjusted over the duration of the heat.



(a) EAF 1



(b) EAF 2

Fig 2: Methane content of the off-gas during one heat

Alongside that Figure 3 shows the simulated hydrogen content of the off-gas during an exemplary heat. In contrast to Figure 2 where the methane content for 100% hydrogen in the fuel gas is equal to zeros, hydrogen is present in the off-gas for all analysed fuel gas compositions. Due to the high temperatures in the electric arc as well as in the furnace atmosphere, diatomic hydrogen gas is formed within the gas phase of the EAF. Therefore, it is also present in the off-gas. One can see that for both EAFs the hydrogen levels in the off-gas are increasing with rising hydrogen levels in the fuel gas. This difference indicates that unburned hydrogen introduced through the burners is present in the off-gas. In EAF 2 the difference is quite small and almost neglectable, as the burners are scarcely operated. For EAF 1 the hydrogen content in the off-gas is rising with increasing hydrogen levels in the fuel gas. At maximum the hydrogen level in the off-gas is doubled between the case of 100% natural gas and 100% hydrogen. However, one has to keep in mind the normalised scale. As the hydrogen content in the off-gas for 100% natural gas is fairly small, the resulting amount for 100% hydrogen is still quite small.

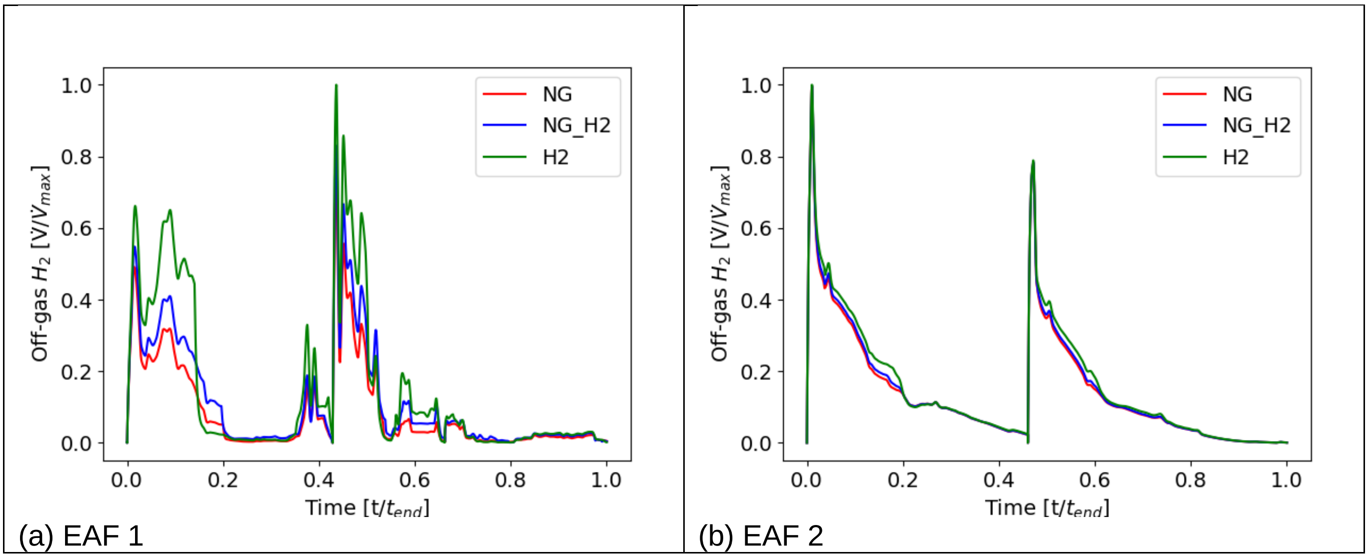


Fig 3: Hydrogen content of the off-gas during one heat

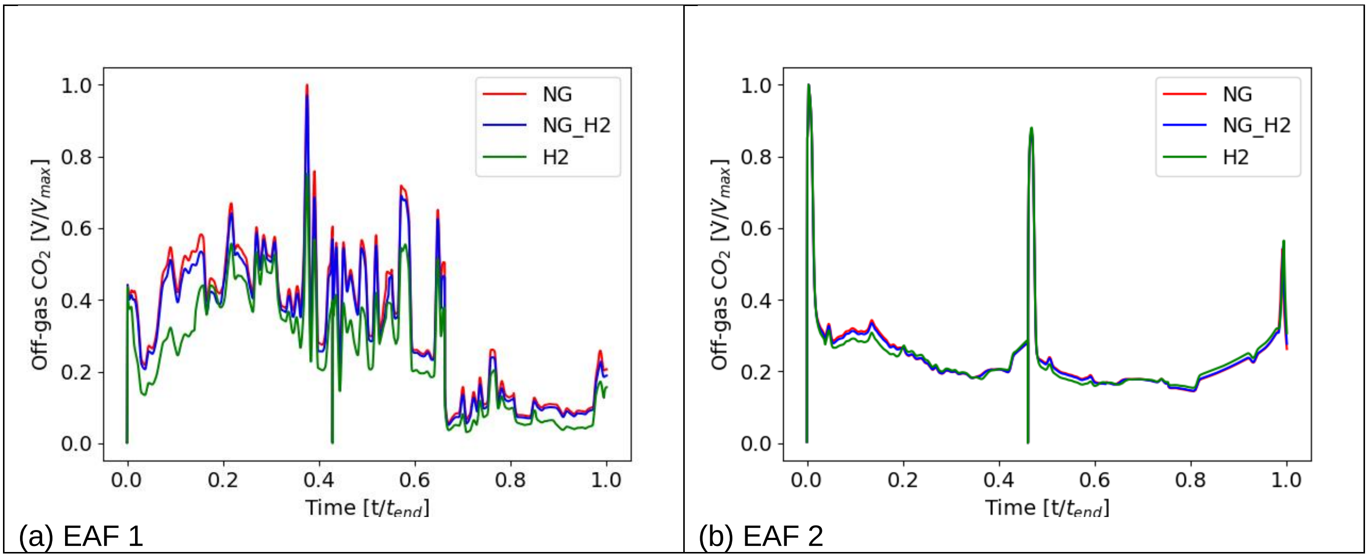
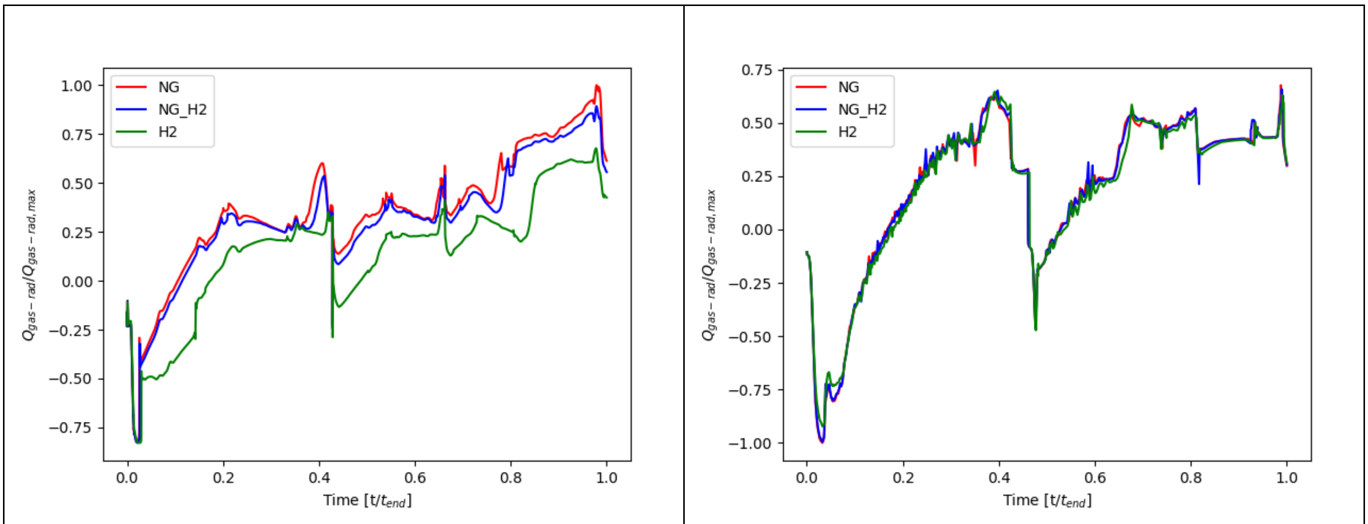


Fig 4: Carbon dioxide content of the off-gas during one heat

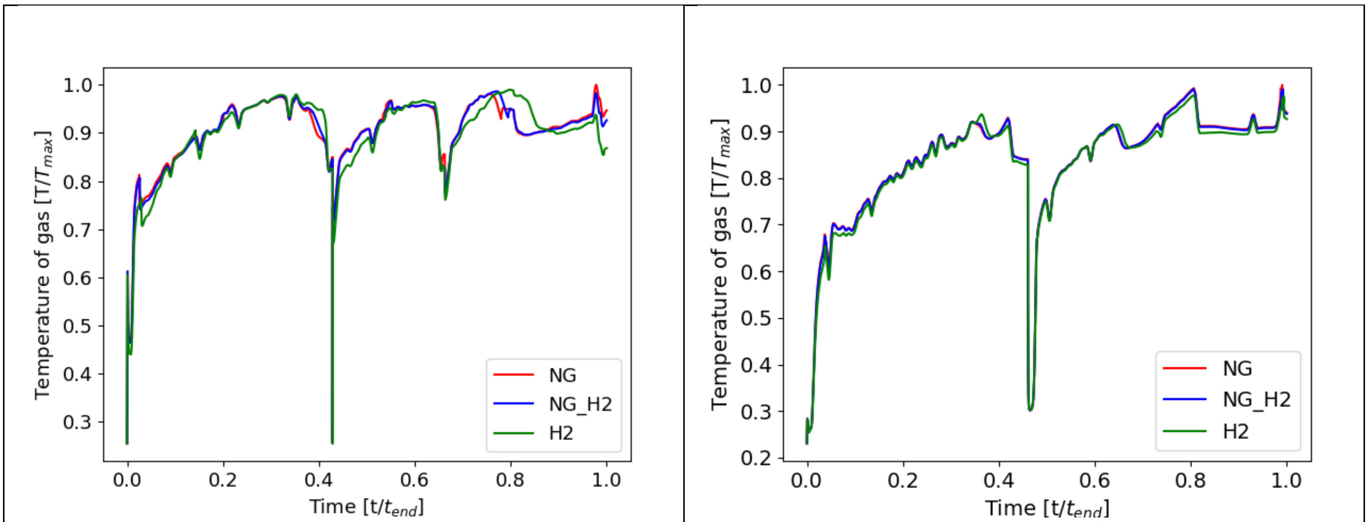
The overall goal of the substitution of natural gas by hydrogen is the reduction of green house gases especially carbon dioxide. Figure 4 shows the simulated carbon dioxide content in the off-gas for both EAFs. EAF 1 shows a significant carbon dioxide reduction in the off-gas with decreasing level of natural gas usage. For the fuel gas mixture of 50 vol-% natural gas and hydrogen the decrease in carbon dioxide emissions is small in comparison to 100% hydrogen. At maximum the carbon dioxide level of the off-gas is three times lower for 100% hydrogen than it is for 100% natural gas. According to this a reduction of up to 10% carbon dioxide is possible by substitution of natural gas with hydrogen. In Figure 4 for EAF 2 it is visible that this is only possible if the burners are frequently operated. For EAF 2 a reduction in carbon dioxide emissions is slightly visible at times of burner operation (e.g. Figure 2). However, almost no difference is apparent in the carbon dioxide emissions.

The change in the composition of the gas zone due to the change in fuel gas composition, also influences the radiative properties of the gas zone. In Figure 5 the simulated net radiation to and from the gas zone to other zones of the EAF process model is shown on a normalised scale. In EAF 2 no difference is visible between the different fuel gas compositions as the burners are used too infrequently to have an evitable effect on the radiative properties of the off-gas. With rising hydrogen levels in EAF 1 the radiative properties of the off-gas vary. The radiative properties of carbon dioxide are responsible for the climate damaging effects of carbon dioxide in the atmosphere. These properties are enhancing the radiation of the gas zone in the EAF. For this reason, the radiative properties of the off-gas are decreasing with rising hydrogen levels in the fuel gas. In the model the dust loading of the gas zone is not considered, therefore the effect of the hydrogen burners may be overestimated.



(a) EAF 1 (b) EAF 2

Fig 5: Radiative properties of the off-gas during one heat



(a) EAF 1 (b) EAF 2

Fig 6: Temperature of the off-gas during one heat

Figure 6 shows the normalised temperature of the off-gas over the course of one heat for the different fuel gas compositions. As one can see the temperature of the off-gas does not change in the EAF process model with different fuel gas compositions for either furnace. This leads to the assumption that the change in radiative properties does not change the overall temperature in the gas zone.

Most important for the EAF operation is the influence of the substitution of natural gas by hydrogen on the temperature of liquid steel, as this temperature dictates the time for tapping. The normalised temperature of liquid steel is shown in Figure 7. For both EAFs the same influence of rising hydrogen levels in the fuel gas is visible, for EAF 1 the effects are better visible as the burners are used more often than in EAF 2. After the first phase where the burners are used, the temperature of liquid steel is higher for higher levels of hydrogen in the fuel gas. This may be accounted to the higher radiative properties of the off-gas with a hydrogen combustion. At tapping this trend changes and the temperature of liquid steel decreases with increasing hydrogen levels. This effect may be referable to the calculations in the model. Within the model, higher temperatures in the beginning of the heat result in an increased energy loss through the water-cooling system and thus are responsible for the lower temperatures at tapping.

In the EAF operation these small differences due to the changes in the fuel gas composition can be cancelled out by adjustments in the operation chart. Furthermore, the shown results featuring a combustion of hydrogen are not validated yet. This validation will be carried out as soon as industrial trials at the investigated EAFs are carried out. An adjustment of the model parameters for the simulation of the hydrogen combustion may be possible.

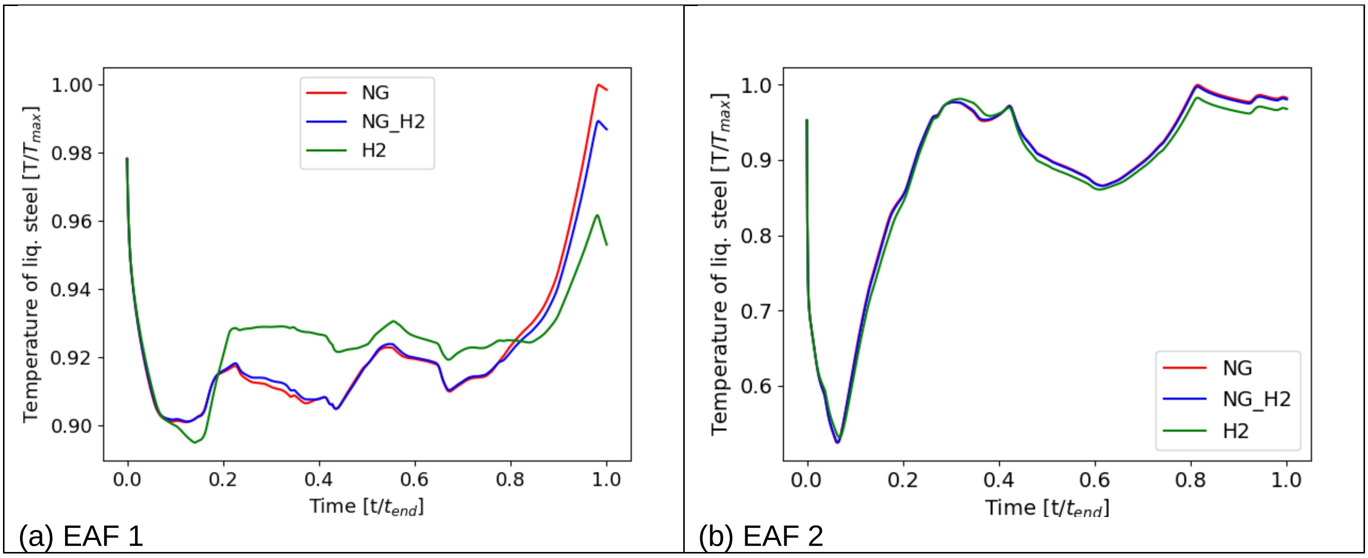


Fig 7: Temperature of liquid steel during one heat

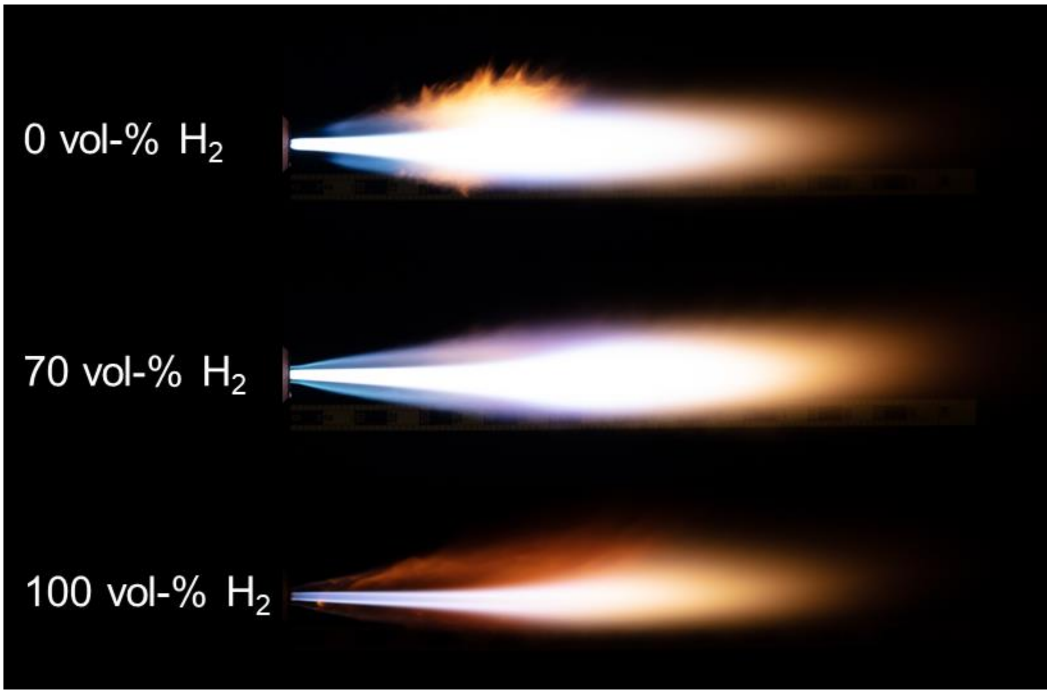


Fig 8: Free flame trials of 50 kW burner

Before the installation of hydrogen fired burners in the investigated EAFs a pilot scale burner will be installed in a pilot scale EAF and will be fired with fuel gas compositions ranging from 100% natural gas to 100% hydrogen. The burner is a scaled-down 50 kW burner which is especially designed for the combustion of natural gas and hydrogen. An analysis of the flame is carried out by free flame trials of this burner with different fuel gas compositions. The results are shown in Figure 8. It is visible that for all fuel gas compositions a long and stable flame is produced. With the addition of hydrogen to the fuel gas the flame increasingly stabilised itself. For all fuel gas compositions, the length of the visible flame is in the same range. Even for the flame with 100% hydrogen in the fuel gas a flame is visible, due to particles present in the ambient atmosphere.

CONCLUSIONS

The described EAF process model is able to simulate the processes inside the EAF. This model is adjusted to be able to investigate the conditions within the furnace induced by the combustion of hydrogen. Two exemplary heats of different EAFs and with different burner usages were investigated for fuel gas compositions ranging from 100% natural gas to 100% hydrogen. The results show that hydrogen fired burners influence the overall process of the EAF operation. These are no major effects and can be cancelled out by small adjustments to the operation chart of the furnace. Nonetheless, the model has yet to be validated for hydrogen combustion by conducting industrial trials. The preliminary results show that with an intensive use of burners a carbon dioxide reduction up to 10% is possible by substitution of natural gas with hydrogen.

Before these industrial trials free flame trials of a pilot scale hydrogen burner are carried out to analyse the flame. With more hydrogen in the fuel gas the flame becomes more stable. Also, the flame length for all fuel gas compositions is sufficient for the application in the EAF. In a next step this pilot scale burner will be installed in a pilot scale EAF and the effects of a hydrogen fired burner on the EAF operation can be further analysed.

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