Hydrogen: reducing fuel-based CO_2 in clinker burning

To reduce carbon dioxide emissions from clinker burning, the cement industry is exploring the use of hydrogen as fuel in the cement kiln. As the product of hydrogen combustion is only water, the theoretical potential exists to reduce CO_2 emissions from the sector by up to a third.

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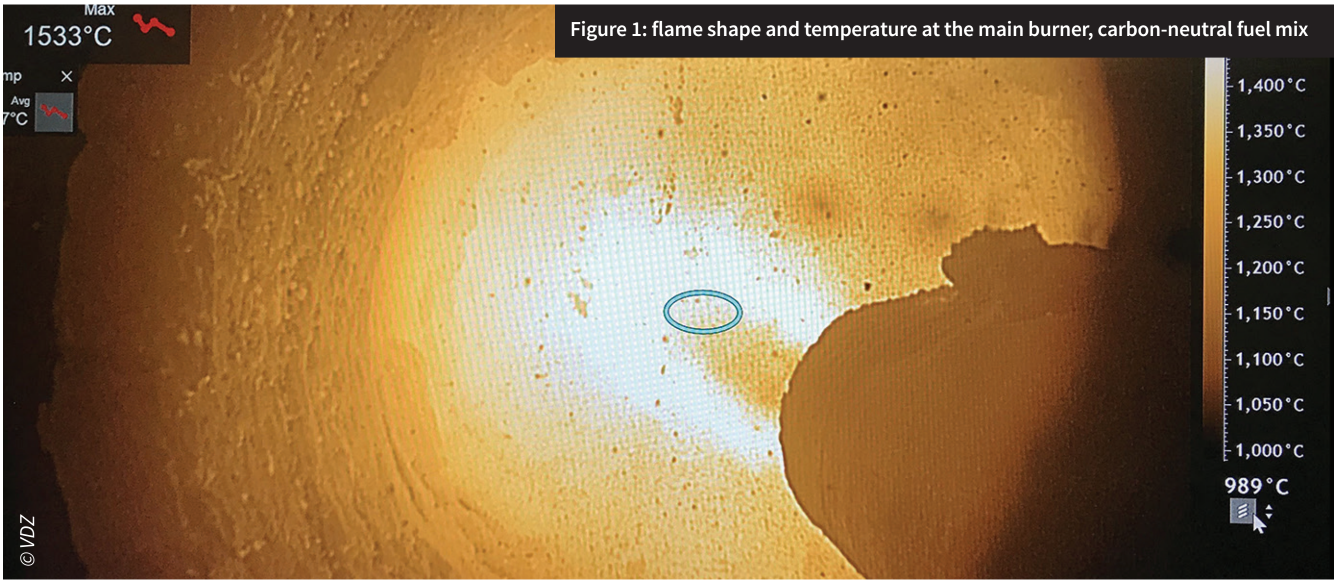

Figure 1: flame shape and temperature at the main burner, carbon-neutral fuel mix

The use of hydrogen gas (H_2) has vast potential to reduce fuel-based carbon dioxide (CO_2) emissions in the cement industry. When hydrogen is combusted, only water is emitted as steam instead of CO_2. If, in theory, all fossil and carbon fuels in the cement industry were replaced by hydrogen, the CO_2 emissions of this industry sector could globally be reduced by one third. However, in practice, alternative fuels, such as RDF, used tyres or dried sewage sludge, will continue to be used in addition to hydrogen.

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One of the biggest challenges is the availability of renewable energy, which is needed for the climate-neutral production of hydrogen. Currently, the use of hydrogen in the cement industry is insignificant.

Cement industry trials and outcomes

The largest known trial in which hydrogen was used in a rotary kiln was carried out in the UK in 2022. The trial was part of the Fuel Switch project (BEIS, Mineral Products Association), in which a rotary kiln was operated with a carbon-neutral fuel mix at the main burner. The fuel mix consisted of an energy share of 40 per cent hydrogen and 60 per cent biomass (glycerine and animal meal) at the primary burner. The result of the short-term test over a few hours was that the technical implementation of using hydrogen as a fuel at the kiln burner is possible without major changes to the burner itself.

Even taking the short test period into consideration, the effects of hydrogen on the burning process were less than expected. Based on preliminary studies, it had been anticipated that the temperature in the centre of the flame would increase due to the higher calorific value and better ignition properties of hydrogen compared to, for example, natural gas. Furthermore, it could not be observed that the flame was drawn closer to the burner tip, radiated less than a carbon-based fuel flame, or that the heat transfer into the clinker bed would decrease (see Figure 1). By increasing the velocity of the hydrogen injection into the kiln, the increase in temperature and also the shift of the flame position could be avoided.

The test period was too short to reliably assess whether the total thermal energy consumption was affected. Compared to coal, hydrogen requires less combustion air related to its energy content, therefore the oxygen demand decreased as the hydrogen substitution rate was increased.

In long-term operation, the kiln firing could be adapted accordingly. When combusting hydrogen with air, the temperature must be adjusted to prevent the formation of thermal NO_x. A slight increase of NO_x was observed, but it could be easily controlled by reducing the total amount of fuel at the main burner. No impact on the clinker quality was visible, taking the short duration of the trial into consideration. Since the introduction of ash from coal into the system decreased, the kiln feed had to be adjusted to compensate for the missing input of Al, Fe and Si.

In the future scenario of 2050, in which a global average share of hydrogen will account for ~10 per cent of the total thermal energy demand (GCCA Concrete Future Roadmap), fuel-based CO_2 emissions will decrease accordingly. To fully evaluate the influence of hydrogen on the clinker burning process and the kiln components, long-term tests are required.

Ensuring a hydrogen supply

Production and transport

In principle, hydrogen can be produced at any place and delivered to the cement plant by truck or train. If large volumes of hydrogen are needed, the connection to a hydrogen pipeline or an in-house hydrogen production is required. The mass-based calorific value of hydrogen (120MJ/kg) is higher than that of coal or oil, but since hydrogen has a very low volume-based calorific value (10.8MJ/m^3), it needs to be highly compressed to provide the same amount of energy in the same dimension. This results in uneconomical transportation.

By producing hydrogen directly on site, the energetically expensive transformation of hydrogen into a highly-compressed stage or even liquifying it (>700bar, needed for transportation) can be largely avoided.

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In contrast to other industries (eg, the automotive industry), the hydrogen produced only has to be compressed at the electrolyser and can immediately be used for combustion after low-pressure storage. Buffer tanks are needed if a continuous use of hydrogen at the kiln is required. If hydrogen is produced locally, a high-voltage power grid connection is also necessary.

Currently, most cement plants do not consider hydrogen use as a viable option due to high hydrogen and/or energy prices as well as limited accessibility to a hydrogen source. Based on different sources, hydrogen prices are assumed to stabilise at around US$1.60/kg (US$13.2/GJ) in 2050. In the ECRA Technology Papers, which summarise different energy efficiency and decarbonation technologies in the cement industry, further remarks on the costs of hydrogen are listed.

The challenge of green hydrogen

Today, hydrogen is mainly produced from natural gas, which classifies the hydrogen as 'blue'. To produce 'green' hydrogen locally, electricity from renewable energy sources is needed, for example from wind turbines. This further contributes to the challenges when green hydrogen is required as a possible fuel source since the production of blue hydrogen is currently cheaper than the production cost of any other low-emission hydrogen. As stated in the Global Hydrogen Review, the average production cost for 1kg hydrogen in 2021 was US$1.00-2.50 for unabated natural gas, whilst the production from natural gas with CCUS costs US$1.50-3.00/kg hydrogen. The production costs for green hydrogen via electrolysis using renewable electricity are expected to be in the range of US$4.00-9.00/kg. These costs reflect the energy demand for production. In 2020 the power demand of PEM membrane- and alkaline electrolyser systems varied between 50-83kWh/kg hydrogen. In contrast, the energy demand to produce blue hydrogen based on natural gas plus CCS amounted to 1.91kWh/kg hydrogen. The stochiometric water demand for blue hydrogen production amounted to 6kg H_2O/kg hydrogen due to the steam reformation process and is on a similar level with the water demand for green hydrogen production with 9kg H_2O/kg hydrogen. On the bright side, the acquisition of electrolysers in the form of container solutions seems to be a viable option and has been successfully tested in many cement plants.

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In the future, the performance of electrolysers is expected to increase. Currently, capillary-fed electrolysis cells are in development which allow efficiencies of up to 95 per cent. Another benefit of using hydrogen electrolysers locally at the plant is that the produced oxygen can be used to enrich the flame, which can lead to increased clinker production. Alternatively, the excess amount of oxygen from the electrolyser can be used, ie, to improve the combustion of alternative fuels in the main burner.

Conclusion

To summarise, the Fuel Switch project has successfully shown that hydrogen can indeed be introduced into the kiln burner without the need for major changes at the burner. Availability and stability of the hydrogen must be ensured through a continuous hydrogen supply. Parameters regarding the hydrogen injection, flame shape and heat radiation mainly influence the overall outcome.

Despite the success of this short-term test, the use of hydrogen as a fuel in the kiln in terms of the effects on the clinker burning process and the clinker quality has to be further investigated in long-term tests. When hydrogen is produced by electrolysis at the plant, the power connection to renewable energy sources must be secured. Furthermore, working with hydrogen requires trained personnel and safety regulations as well as measures to prevent hydrogen leakages into the atmosphere. ■