

Thermodynamic evaluation of different metal-oxide systems for their applicability for hydrogen plasma-based reduction

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Hydrogen gas is a possible replacement for carbon in reduction processes for certain metal-oxide systems such as iron/iron oxide. But several other metal oxides, such as silicon and manganese, cannot be reduced to the metallic state by H₂. By exciting the gas to the plasma state – introducing more reactive species like monoatomic hydrogen (H) – the thermodynamics become favourable for reduction for several of these metals. SINTEF has launched the HyPla project to investigate these opportunities. This paper presents thermodynamic calculations performed to evaluate the promise of some oxide systems for hydrogen plasma reduction.

INTRODUCTION

In many processes, carbon plays an integral part of the metal producing reactions, with CO₂ as an unavoidable by-product:



The options to mitigate these CO₂ emissions can broadly be categorised into:

1. Using sustainably sourced biogenic carbon as the reductant
2. Capturing the emitted CO₂ post-process
3. Replacing the carbon with another reductant (metallothermic, electrolytic, hydrogen)

From category 3, using hydrogen as the reducing agent would lead to steam as a by-product rather than CO₂:



Hydrogen has received a lot of attention in the last few years, playing a major part in most carbon-neutral future scenarios, and is listed by, e.g., the European Commission (European Commission, 2020) as one of few ways to decarbonise iron and steelmaking. Unfortunately, hydrogen is a weaker reductant than carbon, so many metal oxides cannot be reduced after Equation 2.

If the hydrogen is excited to the plasma state, it will contain more reactive species such as monoatomic hydrogen, H, rotationally excited hydrogen, H₂^{*}, and ions such as H₂⁺ and H⁺ (Sabat *et al.*, 2014). These species are much more reactive than H₂, and reduction may, for example, possibly be based on the following reaction:



Equation 3 is thermodynamically favourable for a range of metals/oxides, and across a range of temperatures, whereas Equation 2 is not. As an example, consider the reduction of tantalum oxide:



Calculations in the reaction module of FactSage thermochemical software (Bale *et al*, 2016) shows that at standard conditions, reaction 4 has a positive DG for all temperatures, whereas reaction 5 has negative DG below 2684 °C. Metallisation of Ta₂O₅ by hydrogen plasma has been reported experimentally in literature (Stokes, 1971).

This opens up the possibility of extending the range of metals that can be produced with hydrogen as the reducing agent. SINTEF has initiated the HyPla project to investigate these opportunities (SINTEF, 2020). In this project, SINTEF is building an experimental reactor for investigation of oxide reduction with hydrogen plasma, and the work is supported by modelling efforts. Thermodynamic calculations are required as input to the selection of oxide systems and in the definition of materials properties at the challenging and, as of yet, not well studied conditions in a plasma reactor. Thermodynamics will also be useful in interpreting experimental results.

Oxide selection

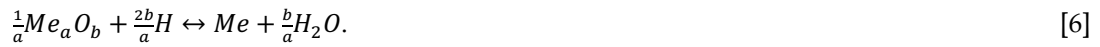
As indicated in the introduction, monoatomic hydrogen is very reactive and can theoretically reduce several relatively stable metal oxides across a wide range of temperatures. Beyond the academic interest, from the point of view of potential for commercialisation, certain metal/oxide systems are of greater interest than others. In the current work, the main motivation to use hydrogen plasma as a reductant is to eliminate CO₂-emissions. Other priorities, such as a desire for a certain product quality/purity may give a different criteria for selection of candidate metal/oxide-systems, but in terms of CO₂-reduction, a good candidate metal/oxide-system is one for which:

- Current production is not without direct CO₂-emissions
- Obvious CO₂-free replacement technologies do not exist
- The reduction potential with H appears promising

With regards to the first point, this excludes for example molybdenum, which is produced from MoO₃ with H₂. Similarly, it can be argued that iron and aluminium could be excluded based on the second point, as H₂ based reduction of iron (SSAB, 2021) and inert anode-based electrowinning of aluminium (Elysis, 2021) are close to industrialisation. For the third bullet point, it is necessary to look into the thermodynamics of the system in question, which is the topic of this paper.

Extent of reaction from equilibrium constant

A reaction between a metal oxide and monoatomic hydrogen to metal and water can be written as:



With the stoichiometric coefficients as written in Equation 6, everything is considered per mole of metal formed. The *extent of reaction* x will be equal to the number of moles of metal formed. The value of x will be a measure of how suitable a metal/oxide-system is for plasma reduction, and gives a quantified way of comparing candidate systems.

Approximating concentrations (written in square brackets) for activities, the equilibrium constant is given by:

$$k = \frac{[Me][H_2O]^{\frac{b}{a}}}{[Me_aO_b]^{\frac{1}{a}}[H]^{\frac{2b}{a}}}. \quad [7]$$

Assuming a starting condition equivalent to a mixture of reactants at stoichiometric ratio as given by Equation 6 (i.e. 1/a moles of Me_aO_b and 2b/a moles of H), the equilibrium coefficient can be expressed in terms of x .

Consider, as an example, the reaction between H and chromium oxide, Cr_2O_3 :



The molar amounts (written in curly brackets) of each component in reaction 8 at extent of reaction $x=0$ is:

$$\{\text{Cr}\}_0 = 0, \{\text{H}_2\text{O}\}_0 = 0, \{\text{Cr}_2\text{O}_3\}_0 = \frac{1}{2}, \{\text{H}\}_0 = 3. \quad [9]$$

And the molar amounts of each component at extent of reaction x is:

$$\{\text{Cr}\}_x = x, \{\text{H}_2\text{O}\}_x = \frac{3}{2}x, \quad \{\text{Cr}_2\text{O}_3\}_x = \frac{1}{2}(1-x), \quad \{\text{H}\}_x = 3(1-x). \quad [10]$$

The concentration of pure condensed phases can be considered unity, so at temperatures below the boiling point of Cr (2672°C), $[\text{Cr}]=1$, $[\text{Cr}_2\text{O}_3]=1$. This means that different expressions must be derived for different temperature ranges depending on what species are gaseous vs. condensed, but below 2672°C we have for the concentrations of H_2O and H:

$$[\text{H}_2\text{O}] = \frac{\{\text{H}_2\text{O}\}}{\{\text{H}_2\text{O}\} + \{\text{H}\}} = \frac{\frac{3}{2}x}{\frac{3}{2}x + 3(1-x)} = \frac{x}{2-x}, \quad [\text{H}] = \frac{\{\text{H}\}}{\{\text{H}_2\text{O}\} + \{\text{H}\}} = \frac{3(1-x)}{\frac{3}{2}x + 3(1-x)} = \frac{2(1-x)}{2-x}, \quad [11]$$

and the equilibrium constant:

$$k = \frac{(x/(2-x))^{\frac{3}{2}}}{(2(1-x)/(2-x))^3} = \frac{x^{\frac{3}{2}}(2-x)^{\frac{3}{2}}}{8(1-x)^3} \quad [12]$$

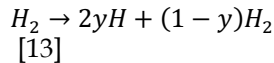
The equilibrium constant for different temperatures can be found using the reaction module of FactSage (Bale *et al.*, 2016). Solving equation [12] for different values of $k(T)$ can thus give the extent of reaction as a function of temperature, $x(T)$.

For some reactions (i.e. for some a and b in Equation 6) and some temperature ranges where the 'right number' of phases are condensed, the expression equivalent to that of Equation 12 can be solved analytically. In other cases, such as the example case for Cr/ Cr_2O_3 , an analytical solution is very complicated, but a numeric solution can be found. In this work, regardless of the nature of the expression for k as expressed as a function of x , it has been solved using the 'solver' function of Microsoft Excel: by minimising the square error $(k(T) - k(x))^2$ by varying x ; $k(T)$ being the equilibrium constant as found from FactSage, and $k(x)$ being an expression derived in a similar way as that of equation [12].

Extent of reaction for different degrees of plasma excitation

In the derivation above, it is assumed that H, H_2O , Me and Me_aO_b are the only species present when calculating the concentrations and the equilibrium constant expressions. In a real system, not all H_2 will be excited to H, and so some amount of H_2 would also be present.

Let y be the fraction of hydrogen that is excited:



Since the metal/oxide systems that are of most interest are systems where H_2 does not efficiently reduce the oxide, it is a decent approximation to assume that the unexcited H_2 is inert. In this case, the equilibrium constant will still be given by Equation 7. The concentrations however, will be different. Taking again the Cr/ Cr_2O_3 -example, if a fraction y of the hydrogen is excited, the molar amounts of each component at extent of reaction 0 is:

$$\{\text{Cr}\}_0 = 0 \quad \{\text{H}_2\text{O}\}_0 = 0 \quad \{\text{Cr}_2\text{O}_3\}_0 = \frac{1}{2} \quad \{\text{H}\}_0 = 3y \quad \{\text{H}_2\}_0 = \frac{3}{2}(1-y),$$

and at extent of reaction x we have:

$$\{Cr\}_x = xy \{H_2O\}_x = \frac{3}{2}xy \quad \{Cr_2O_3\}_x = \frac{1}{2}(1 - xy) \{H\}_x = 3y(1 - x) \quad \{H_2\}_x = \frac{3}{2}(1 - y) \quad [14]$$

The extent of reaction x now gives the fraction of the excited hydrogen that reacts, which means that x which means that the amount of metal produced is no longer solely dependent upon x , but is now given by the product xy .

Below the boiling point of Cr, [Cr] and [Cr₂O₃] are still in unity, but the concentrations of H and H₂O are modified by the presence of H₂:

$$[H_2O] = \frac{\frac{3}{2}xy}{\frac{3}{2}xy + 3y(1-x) + \frac{3}{2}(1-y)} = \frac{xy}{1+y-xy}, \quad [H] = \frac{3y(1-x)}{\frac{3}{2}xy + 3y(1-x) + \frac{3}{2}(1-y)} = \frac{2y(1-x)}{1+y-xy}, \quad [15]$$

and so the equilibrium constant becomes

$$k = \frac{\left(\frac{xy}{(1+y-xy)}\right)^{\frac{3}{2}}}{\left(\frac{(2y(1-x))}{(1+y-xy)}\right)^3} = \frac{x^{\frac{3}{2}}(1+y-xy)^{\frac{3}{2}}}{8y^{\frac{3}{2}}(1-x)^3} \quad [16]$$

(Which reduces to Equation 12 for $y = 1$.)

By choosing different values for y , it is possible to calculate $x(y, T)$ by numerically fitting $k(y, x)$ to $k(T)$ as before, and thus estimate the extent of reaction as a function of degree of excitation of plasma.

Table I. Overview of equilibrium constant expressions, $k(x, y)$, for different metal oxide reduction reactions considered in the current work

| CASE | Chemical equation | Equilibrium constant, $k(x, y)$ |
|------|--|--|
| A | $MeO_{(l/s)} + 2H_{(g)} \rightarrow Me_{(l/s)} + H_2O_{(g)}$ | $k = \frac{x(1+y(1-x))}{4y(1-x)^2}$ |
| B | $MeO_{(l/s)} + 2H_{(g)} \rightarrow Me_{(g)} + H_2O_{(g)}$ | $k = \frac{x^2}{(2(1-x))^2}$ |
| C | $\frac{1}{2}Me_2O_3_{(l/s)} + 3H_{(g)} \rightarrow Me_{(l/s)} + \frac{3}{2}H_2O_{(g)}$ | $k = \frac{x^{\frac{3}{2}}(1+y-xy)^{3/2}}{8y^{\frac{3}{2}}(1-x)^3}$ |
| D | $\frac{1}{2}Me_2O_3_{(l/s)} + 3H_{(g)} \rightarrow Me_{(g)} + \frac{3}{2}H_2O_{(g)}$ | $k = \frac{x^{\frac{5}{2}}\left(1+y\left(1-\frac{x}{3}\right)\right)^{\frac{1}{2}}}{12y^{\frac{1}{2}}(1-x)^3}$ |
| E | $MeO_{2(l/s)} + 4H_{(g)} \rightarrow Me_{(l/s)} + 2H_2O_{(g)}$ | $k = \frac{x^2(y-xy+1)^2}{16y^2(1-x)^4}$ |
| F | $MeO_{2(l/s)} + 2H_{(g)} \rightarrow MeO_{(g)} + H_2O_{(g)}$ | $k = \frac{x^2}{4(1-x)^2}$ |
| G | $MeO_{(g)} + 2H_{(g)} \rightarrow Me_{(l/s)} + H_2O_{(g)}$ | $k = \frac{x(1+2y-2xy)^2}{4y^2(1-x)^3}$ |
| H | $\frac{1}{2}Me_2O_3_{(l/s)} + \frac{3}{2}H_2_{(g)} \rightarrow Me_{(l/s)} + \frac{3}{2}H_2O_{(g)}$ | $k = \left(\frac{x}{1-x}\right)^{\frac{3}{2}}$ |
| I | $\frac{1}{2}Me_2O_3_{(l/s)} + \frac{3}{2}H_2_{(g)} \rightarrow Me_{(g)} + \frac{3}{2}H_2O_{(g)}$ | $k = \frac{x^{\frac{5}{2}}}{(1-x)^{\frac{3}{2}}\left(\frac{3}{2}+x\right)}$ |

The different metal/oxide systems will have different equilibrium constant expressions $k(x,y)$. Deriving them all by the method exemplified in Equations 14-16 is left out of the current text, and the resulting expressions are summarised in Table I.

In some applications it is likely that the plasma gas will be a mixture of hydrogen and another gas, such as Ar. This will not change the expressions described above noticeably. Since it has been assumed that H_2 is not chemically active, the expressions above can be used simply by implementing

$$\{H\}_0 = 3y \quad \{H_2\}_0 + \{Ar\}_0 = \{H_2\}_x + \{Ar\}_x = \frac{3}{2}(1-y) \quad \{H\}_x = 3yx \quad [17]$$

In other words, y is now the fraction of the total gas phase that is converted to H, and it is limited by $y \leq \{H\}_0 / (\{H\}_0 + \{Ar\}_0)$ but otherwise the expressions are the same.

Extent of reaction for selected metal/oxide systems

Manganese

The higher manganese oxides like Mn_2O_3 and MnO_2 can be reduced by H_2 gas, but not MnO . The equilibrium constant for MnO -reduction by H is given by Case A from Table 1 below $2062^\circ C$ and Case B above $2062^\circ C$. Figure 1A shows the extent of reaction as a function of temperature for two different fractions of excitation (=values of y). The extent of reaction is high for all temperatures for both values of y . There is a decrease in the calculated extent of reaction as the temperature approaches the boiling point of manganese, at which the plots make a jump and there is a discontinuity. This is an artifact due to the assumptions made. Manganese has a substantial vapour pressure, and so the assumption that all produced manganese exists as a condensed phase with concentration 1 is incorrect. A refined calculation could take into account the equilibrium vapour pressure of manganese in the product phase. At temperatures above $2062^\circ C$, the extent of reaction is independent of y (ref Case B in Table I), and so the plots overlap.

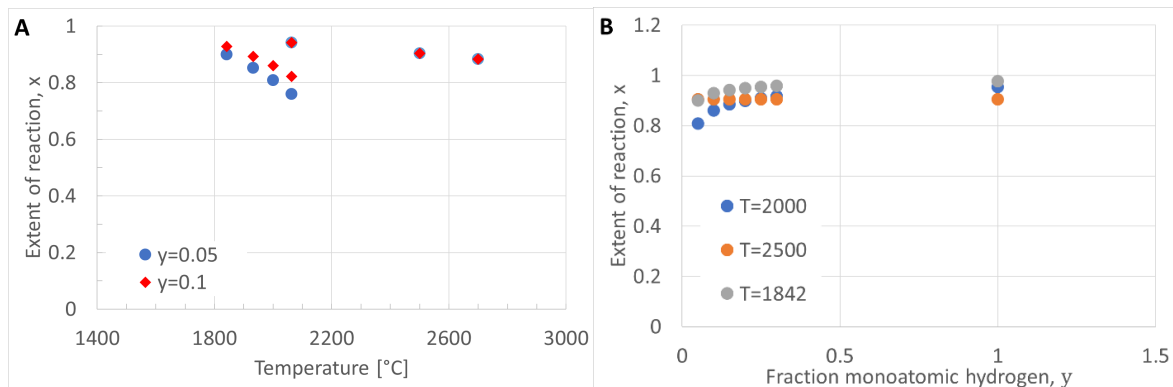


Figure 1. Extent of reaction for reduction of MnO by monoatomic hydrogen. A: As a function of temperature for two different fractions y of monoatomic hydrogen. B: As a function of fraction y of monoatomic hydrogen for three different temperatures.

Figure 1B shows extent of reaction as function of y at two different temperatures. It is seen that the extent of reaction dips slightly for lower levels of H in the plasma, but the decrease is not dramatic. A far greater impact on the degree of metallisation will be due to the greater amount of H available for reaction at higher y .

Chromium

Chromium oxide, Cr_2O_3 , can be reduced by hydrogen gas, but the reaction halts at very small values of p_{H_2O}/p_{H_2} (Chu & Rahmel, 1979) and as such practical applications are challenging. Here, a comparison between reduction by H_2 and H is given. The extent of Cr_2O_3 -reduction by H is a case C from Table I below $2672^\circ C$, and a case D above this temperature. It should be noted that the calculations presented here do not take into account the partial decomposition of Cr_2O_3 to CrO and CrO_2 occurring from $2689^\circ C$

according to FactSage. For the case of molecular hydrogen, reduction of Cr_2O_3 is described as case **H** or **I** from Table I, below or above 2672°C respectively.

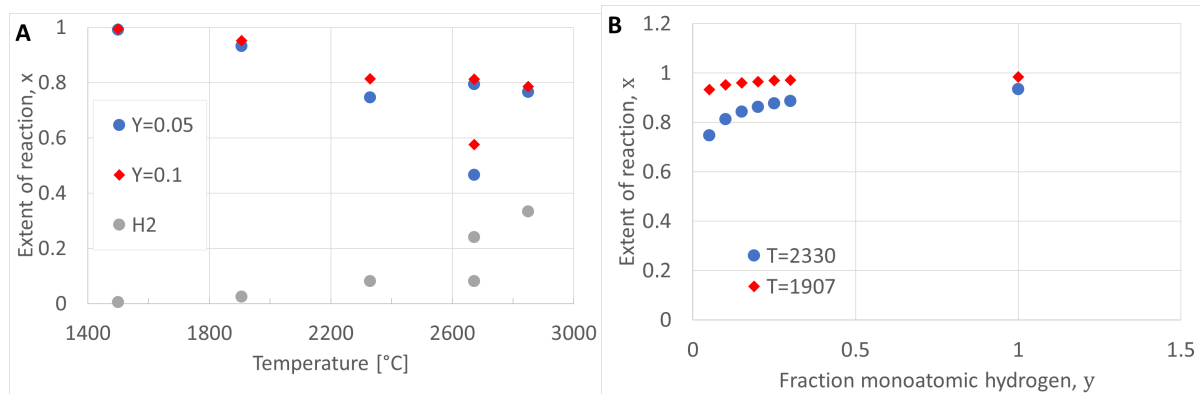


Figure 2. Extent of reaction for reduction of Cr_2O_3 by H_2 and H. A: As function of temperature for H_2 and two different fractions y of monoatomic hydrogen. B: As function of fraction y of monoatomic hydrogen for two different temperatures.

Figure 2A shows the extent of reaction for Cr_2O_3 reduction by H plasma at $y=0.05$ and $y=0.1$, as well as with pure H_2 , while Figure 2B shows the extent of reaction as a function of y (reduction with H_2 obviously not included in this graph). The difference in reduction potential between H and H_2 , as displayed in Figure 2A, is stark, particularly below 2000°C , where there is an extent of reaction above 0.9 with H compared to below 0.1 for H_2 . As was the case for manganese, there is a slight increase in the extent of reaction for increasing values of y , seen from Figure 2B.

However, when the amount of plasma available for reaction is taken into account, and one looks at the degree of metallisation, the picture changes somewhat, as is seen in Figure 3. At higher temperatures the high degrees of metallisation are counterbalanced by the low concentrations of [H], but at temperatures below 2000°C plasma reduction gives greater metallisation by a factor 2-10 or more.

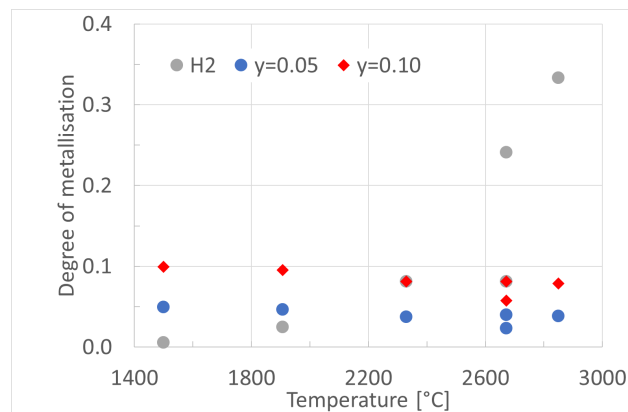


Figure 3. Degree of metallisation for Cr_2O_3 reduction with molecular H_2 and two concentrations of monoatomic hydrogen.

In the $\text{H}_2\text{-H-Cr}_2\text{O}_3\text{-Cr}$ system at intermediary temperatures, it is possible that a more accurate picture could be drawn by taking into account the contribution from both H-reduction and H_2 -reduction. Attempting to solve for two different extents of reactions for both equilibrium constant expressions simultaneously is not a viable method however, as that implicitly fixes the ratio between H_2 and H. This problem has not been explored further in the current work.

Titanium

TiO₂ is a very stable oxide that is challenging to reduce into metallic titanium. Its potential reduction by H follows case E in Table I. The extent of reaction for $y=0.05$ and $y=0.1$ are shown in Figure 4A. Below 2000°C the extent of reaction is significant, but it drops precipitously at higher temperatures, to a much greater degree than in the Cr₂O₃/Cr and MnO/Mn systems, reflecting the stability of TiO₂. Once again Figure 4B shows that the extent of reaction increases with y .

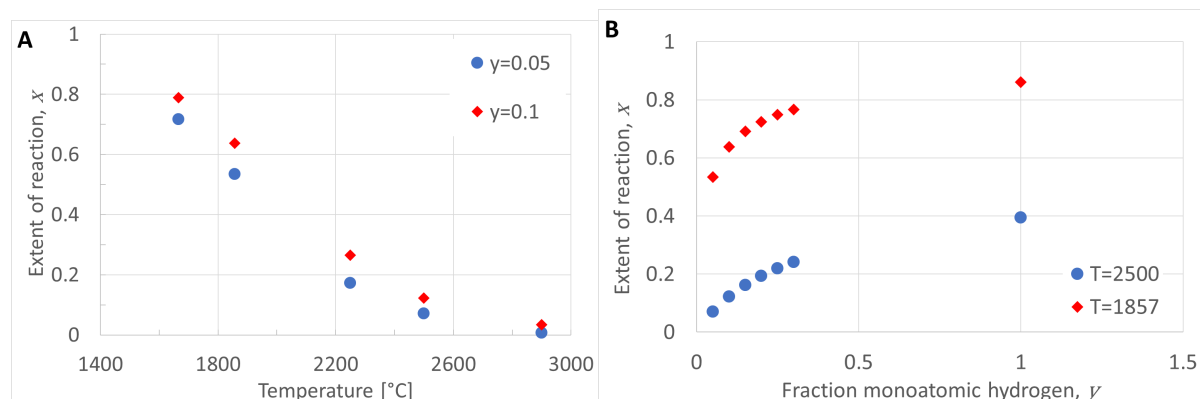


Figure 4. Extent of reaction for reduction of TiO₂ by monoatomic hydrogen. A: As function of temperature for two different fractions y of monoatomic hydrogen. B: As function of fraction y of monoatomic hydrogen for two different temperatures.

Silicon

The direct reduction of SiO₂ to H can be described by an equation of the form E from Table I. However, the intermediate oxide, SiO, is gaseous in nature and stable at high temperatures. The reduction is therefore considered in two steps, first a reduction of SiO₂ to SiO according to case F in Table I, followed by reduction of SiO to Si according to case G. The extent of reaction for the two steps of the reaction are shown in Figure 5A and 5B. The production of SiO-gas from SiO₂ and H is very favourable, but the further reduction of SiO into metallic silicon not so much. At temperatures above $\approx 2000^\circ\text{C}$, there is almost no Si-production, due to the stability of SiO-gas. The production of Si from SiO₂ with hydrogen plasma thus seems dependent on operating at lower temperatures, where metallisation will still be low. With both SiO₂ and SiO in the system, if the amount of H is limited it must be expected to react preferentially with SiO₂ over SiO, and so metallisation may be even lower. The gaseous nature of SiO-gas can also prove practically challenging, as it may drift away from the reaction zone. Perhaps this property can provide a bit of a silver lining to the situation, in that it can be imagined that SiO gas produced from SiO₂ in one region drifts away from where it was produced and into a region where the competing reaction between H and SiO₂ is less of an issue. Nevertheless, the overall picture for silicon appears challenging. As a final note on Si/SiO/SiO₂: For the SiO to Si reduction, the extent of reaction increases with y , as seen in Figure 5B, similar to several other systems. The SiO₂→SiO reduction, being described by Case B in Table I, is independent of y , much the same as for manganese above 2062°C.

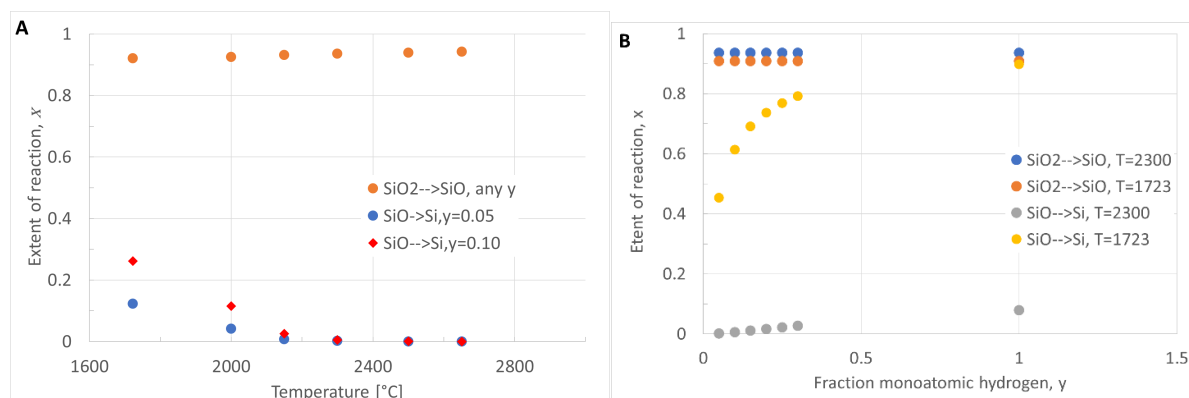


Figure 5. Extent of reaction for reduction of SiO₂ to SiO and of SiO to Si by monoatomic hydrogen. A: As a function of temperature for two different fractions y of monoatomic hydrogen. B: As a function of fraction y of monoatomic hydrogen for two different temperatures.

Required materials parameters

The calculations and considerations presented so far deal with theoretical reaction equilibria, and the next step will be to investigate these in real experiments and with more sophisticated models.

Due to the extreme conditions in a plasma reactor, e.g., with regards to high temperature and short length- and time-scales of flow phenomena, it is very challenging (not to say impossible in some cases) to perform direct measurements of parameters such as flow velocity, temperature, and chemical composition. It is therefore necessary to use different mathematical modelling tools to obtain the necessary insights to the experimental conditions. Similar models will also be needed for any scale-up to an industrial scale.

The successful implementation of such models requires accurate materials property data, such as mass density, specific heat capacity, viscosity, thermal conductivity, electric conductivity, and chemical reaction rates for the gas-plasma mixture. Except for pure gasses and standard gas mixtures (e.g., air), at standard conditions, these materials' data are not readily available in the scientific literature. Plasma-based metal production will require improved availability of materials property data for non-standard mixtures. Due to the obvious difficulties of obtaining experimental results at the extreme temperatures expected in a metallurgical plasma reactor, kinetic theory, statistical thermodynamics, and first principles modelling are required to establish materials property models. In the HyPla project, there is ongoing activity to establish a materials property modelling framework that will be coupled with computational fluid dynamics models. A detailed description of this activity is however beyond the scope of this paper.

Discussion and future work

The calculations above show that it is theoretically possible to produce metals by reduction by monoatomic hydrogen, in cases where those oxides are not reduced by H₂ easily or at all. Perhaps not surprisingly, relatively less stable oxides are predicted to more easily react with H than more stable oxides like TiO₂.

The extent of reactions are predicted to decrease with increasing temperatures (Figures 1, 2, 4, 5), likely due to the increased stability of monoatomic H at higher temperatures, making it less reactive. Increased levels of H in the plasma also increases extent of reaction (in some cases it is independent), so a greater degree of excitation of the plasma will be doubly beneficial: more H will be available for reaction, and a greater fraction of the H present will react. The optimal conditions then, will be lower temperatures and a higher degree of excitation of the plasma. In thermal equilibrium, however, 2400°C is required for 5% H and 2600 for 10% H in a H-H₂ gas mixture. The recombination of 2H → H₂ does require some amount of time (Dayal & Sadedin, 2003), so it possible that a metastable plasma can travel from its point

of generation to a cooler oxide while maintaining a higher-than-equilibrium level of H. Without such a solution, it seems very hard to obtain reduction of TiO_2 , not to mention $\text{SiO}_2 \rightarrow \text{SiO} \rightarrow \text{Si}$.

Chromium and manganese both see application in the steel industry as ferrochrome and ferromanganese alloys respectively. Both Cr and Mn have an affinity for iron, and would be stabilised in a Fe-Cr/Fe-Mn melt relative to their pure states. It is therefore possible that the presence of iron would improve the reduction properties of $\text{Cr}_2\text{O}_3 \rightarrow \text{Cr}$ and $\text{MnO} \rightarrow \text{Mn}$. This could be achieved either by a co-reduction of a mixture of iron oxide with chromium/manganese oxide, or by adding already reduced metallic iron to the system. An interesting continuation of the investigations described herein would be to examine how the reduction potential of Cr_2O_3 and MnO by H changes when the product is a ferroalloy. This could be achieved by using the solution databases of FactSage to calculate the relevant activities.

The calculations presented here by their nature as thermodynamic calculations take no account of kinetics or time dependence. A system where a reacting gas-phase flows past a stationary oxide/metal mixture could be modelled by assuming that a certain fraction of the gas volume reacts to equilibrium during each time step and that all gaseous products are removed from the system and replaced by gas of bulk composition. This could give some information about developments over time, although it would require several assumptions that could be hard to make.

A similar but slightly more complex approach would be to expand the model - not only to time but also to space - by using a reactor network model. Here, the volume of interest is divided into a number of 'reactors' that each obtain equilibrium within each time-step, and there is an exchange of mass and energy between each reactor and between each time step. These types of simulations could be carried out using Macro processing in Factsage, the ChemApp application, or HSC Sim.

More detailed models incorporating reacting flows and CFD models will require the materials property framework mentioned in the section 'Required materials parameters'.

Finally, it should be mentioned that actual experiments must also be run. At the time of writing, these are planned in the HyPla project and are expected to be well under way by the time this paper is presented.

CONCLUSIONS

It is theoretically possible to reduce metallic oxides with monoatomic hydrogen, also in cases where those oxides are not reduced by molecular H_2 . The relatively less stable oxides of chromium (Cr_2O_3) and manganese (MnO) show more reactivity towards H than more stable oxides like TiO_2 .

The extent of reaction decreases with increasing temperature. It generally increases with increasing levels of H in the plasma, although in some cases x is independent of y .

For TiO_2 and SiO , the drop in reactivity with temperature is very pronounced, and it seems as if it is necessary to find a 'sweet spot' where the extent of reaction is reasonably high while it is still possible to maintain adequate levels of excited monoatomic H.

While the reactivity of MnO and Cr_2O_3 also drops with temperature, these curves are much flatter, and these systems appear more forgiving.

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Halvor Dalaker earned his MSc in physics and PhD in Materials Science from NTNU and has worked at SINTEF since 2009. His research interests include circular economy and decarbonisation of metallurgy as well as several others, with thermodynamic calculations often being the common denominator.

Halvor is the project manager of the research project HyPla, which explores the possibility of using hydrogen plasma to produce metal from oxides too stable to be reduced by gaseous hydrogen.