

Steel Wool Rusting in Pure Oxygen Atmosphere: A Simple Kinetic Experiment

Nataša Stavrevska, Vladimir M. Petruševski* and Vladimir Ivanovski

Institute of Chemistry, Faculty of Natural Sciences and Mathematics, Ss Cyril and Methodius University, Arhimedova 5, PO Box 162, 1000 Skopje, Republic of Macedonia, vladop@pmf.ukim.mk

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Abstract: Under isothermal condition the rusting of steel wool (catalyzed by rinsing in saturated aqueous solution of ammonium chloride) follows, almost ideally, a zeroth order kinetics.

Introduction

The present experiment was inspired by experiments aimed to determine the content of oxygen in the air. The latter experiments are quite numerous in the literature [1–15]. It is the steel wool rusting [9, 11, 13] versions of the above task that actually inspired us to think about the experiment we offer here. The standard approach would be to rinse the steel wool with diluted acetic acid and then to place it under a graduated cylinder filled with air. The volume contraction then gives the volume of oxygen in the air, and the ratio of this and the total volume usually gives a good estimate of the percentage of oxygen in air.

The experiment of steel wool rusting, as described above, has one shortcoming: the acetic acid actually reacts with the iron liberating hydrogen. This reaction is somewhat slow, but it exists as a parasite reaction to the one desired (the rusting), so in addition to the volume decrease due to oxygen consumption, there is a slight volume increase due to hydrogen generation. The error might vary within certain limits but it is inevitable.

Thinking about possible replacement for the acetic acid, we tried saturated aqueous solution of NH_4Cl . The reaction of corrosion is slower, but we checked there is practically no hydrogen generation (despite the slightly acidic character of the solution, due to hydrolysis) and this is definitely a certain advantage over the usage of acetic acid. It appeared that the experiment is useless as a lecture experiment for determination of the oxygen content (many hours are needed for the reaction to be completed), but it was possible to offer an original kinetic experiment of steel wool rusting, providing the air was replaced by pure oxygen from a tank. In this way, it complements our previous contributions devoted to the study of kinetics, using relatively cheap equipment [16, 17]. The idea was to check the rate of rusting under conditions of constant pressure (and therefore constant concentration) of oxygen, so any changes in the rate would be related to the change of the surface of the steel wool.

The experiment we propose here lasts up to 24 hours, so it is one more example of marathon experiments [16–22]. Like its predecessors [16, 17], the proposed experiment may be considered as a short marathon experiment.

Experimental

We use saturated aqueous solution of ammonium chloride (after saturation is reached, the excess of the non-dissolved solid NH_4Cl is removed by simple decantation) and steel wool. The equipment we assembled is shown in Figure 1.

Performing the experiment. A piece of steel wool is soaked with concentrated $\text{NH}_4\text{Cl}(\text{aq})$ and is placed inside the reaction chamber (a modified large wash-bottle) containing about 10 mL of the concentrated $\text{NH}_4\text{Cl}(\text{aq})$ solution. Parts 1 and 3 (cf. Figure 1) were then filled with pure oxygen. It is important that parts 1 and 3 are hermetically closed, so any decrease in pressure in the reaction chamber (due to consumption of oxygen, as a result of rusting) will be balanced by flow of water in the graduated cylinder, 3, from the reservoir, 4.

A computer controlled digital camera (Philips ToUcam XS) was adjusted for taking a photo of the above setup every 5 minutes. In this way it was possible to monitor the level of water (colored water, using some food coloring, works best; a permanganate solution is an acceptable alternative) in the graduated glass cylinder with time. The quality of the photos is moderate (640×480 pixels) but completely serves the purpose of reading the volume contraction precisely.

Results and Discussion

It took about 6 hours for the graduated cylinder to be filled with water up to the highest mark on the scale. The temperature of the laboratory was 21°C and was practically constant during the mentioned period. The pressure was 746 Torr in the beginning of the experiment, but 744 Torr in the end. This variation of the pressure is roughly 1.3 % of the total variation of the pressure that would occur if the reaction chamber was hermetically closed (one would expect a decrease of the pressure of some 150 Torr [17]) and could be considered as a minor one.

It took some time till a steady inflow of water was established, due to uncontrolled leaking of water from the tube in the graduated cylinder in the beginning of the experiment. The moment this was established (45 minutes from start), was taken as 'zero time'. The corresponding 'zero volume' corresponds to mark 19 on the scale (cf. Figure 2). Due to the way the scale is drawn (higher values at the bottom of the graduated cylinder), the actual volume (in arbitrary units) is given as $19 - V_{\text{measured}}$.



Figure 1. Equipment for determination of the rate of steel wool rusting. 1 – reaction chamber; 2 – steel wool; 3 – graduated glass cylinder; 4 – reservoir of water.



Figure 2. The so-called 'zero volume', 45 minutes after the experiment begun. All measurements are referred with respect to it.

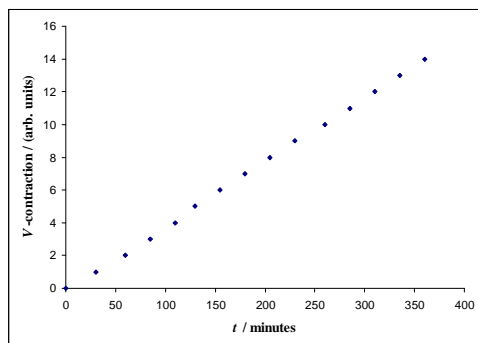


Figure 3. Variation of the volume contraction with time and the equation of the best-fit line.

The experimental pairs of values are presented on the graph in Figure 3. The best-fit line was forced to pass through the origin, in order to retain full physical significance (the regression coefficient, R^2 , is slightly better, at 0.9994, if a two-parameter straight line is fitted).

$$V/(\text{arb. units}) = 0.0394 t/\text{min} \quad R^2 = 0.9975 \quad (1)$$

The variation reveals almost perfect linear dependence, thus revealing zero-order kinetics. This finding indicates that oxygen is the limiting reagent, and by keeping its concentration (i.e. the partial pressure) constant, the reaction

rate is also constant. The results should be markedly different with air, if used instead of pure oxygen, because in that case the concentration of oxygen would clearly decrease down to 0. The corresponding experiment was tried and it was clear that the reaction rate decreases with time. However, its duration is much longer and the variations of the external pressure in the atmosphere prevented us to obtain meaningful results. Anyway, the similarity of the end results for the kinetic in this experiment and in the previous one [16] suggests a possibility for generalization, whenever a pure metal reacts with a limited amount of other reagent (i.e. oxygen or water vapor) providing the concentration of the latter is kept constant. This remains to be checked by further experiments.

Conclusion

The reaction of the steel wool rusting in pure oxygen atmosphere follows zero order kinetics.

Safety Tips and Disposal

Pure oxygen is a strong oxidizer! When performing manipulations with it, remove any flammable material from the immediate surrounding.

References and Notes

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