Experimental and Computational Heat Losses for a Small Dish Receiver

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Abstract

Experimental and computed losses and reactor tube temperature profiles are presented for three ammonia receiver/reactor geometries operating on a 9 m² dish concentrator. Preliminary analysis of receiver losses indicates that as the half cone angle of the receiver tube frustum reduces – from 17.5º to 7.5º to 3.7º – there is a shift from convection-dominated losses to radiation-dominated losses. The convection-dominated losses decrease because the receiver becomes more inverted towards solar altitudes of 90º, while the radiation-dominated losses increase because the reactor tube temperature increases.

1. Introduction

This paper presents experimental and computational heat losses for an ammonia thermochemical receiver operating on a 9 m² dish concentrator – pictured in Figure 1 – and follows on from previous work presented by Dunn et al [1]. The ammonia storage system is based on the reversible dissociation of ammonia, as illustrated in Figure 2, and has been discussed in detail in previous publications [2]. One challenge posed by this system is the high pressure storage of the product gases at 10-30 MPa, compared to commercial storage with molten salt which operates at close to atmospheric pressure [3]. Other thermochemical storage systems under development avoid the storage of gases [4, 5].

The purpose of masking the small dish in Figure 1 was to obtain the same rim angle as the 489 m² SG4 dish concentrator also operated at the Australian National University (ANU) [6]. Three receiver geometries were investigated with half cone angles of 17.5º, 7.5º and 3.7º, as illustrated in Figure 3.

2. Experimental Losses

In previously published work [1], the solar-to-chemical efficiencies obtained for each of the three receiver geometries over a range of operating conditions was presented. An efficiency increase of up to 6.4% absolute was obtained for the geometry with the best performance (7.5º half cone) compared to the worst (17.5º half cone). This section presents preliminary analysis of both the total system losses and the receiver losses.
Fig. 2. Energy storage using dissociated ammonia (nitrogen and hydrogen gas) as the storage medium at ambient temperature.

\[ 2\text{NH}_3 + \Delta H \rightleftharpoons N_2 + 3\text{H}_2 \]

![Diagram showing energy storage using dissociated ammonia](image)

Fig. 3. Three receiver configurations. **Top:** Receiver with the original 17.5° half cone angle (all insulation removed). **Middle:** Receiver with a 7.5° half cone angle (viewed looking into the aperture with the front shield removed). The indents in the wall insulation indicate the position of the tubes in the frustum with a 17.5° half cone angle. **Bottom:** Receiver in a frustum with base radius 77 mm and half cone angle 3.7° (front shield removed), which is approximated by a cylinder of 77 mm radius in the OptiCAD ray-tracing in Figure 13. **Right inset:** Receiver with half cone angle 3.7° viewed looking into the aperture with the front shield in place.
associated with each receiver configuration. The difference in definition between receiver losses and total system losses is illustrated in Figure 4. Receiver losses include only reflection and heat losses from the receiver, while total system losses also include reflectivity and tracking losses for the dish, flux spillage losses, and losses from the heat exchanger and associated piping. Figures 5 to 7 show the total system losses and receiver only losses for each of the three receiver geometries operated in their optimal flow rate ranges. The plots against solar altitude and average tube temperature (Figures 5 and 6) share a common structure:

- linear trendlines for each receiver configuration and flow rate, with
- a positive slope for the 3.7º half cone.
- a slightly negative slope for the 7.5º half cone.
- a steeper negative slope for the 17.5º half cone.

The slope closest to zero in the plot of total system losses with respect to altitude – for the 7.5º half cone – leads to the highest solar-to-chemical efficiencies, as recorded in a previous study [1]. The similarity between the plots of losses with respect to solar altitude and average tube temperature is not surprising. In these experiments, there was an approximately linear relationship between solar altitude and temperature as they were conducted at constant mass flow rate – see Figure 8.

In contrast, the plot of total system losses with respect to wind speed (Figure 7) does not display any trends. This is quite possibly due to the very low wind speeds recorded in these experiments. An experimental study into forced convection losses by Taumoefolau showed distinctly non-linear behaviour of total convection losses compared to wind speeds below 5 m/s [7]. In contrast, at wind speeds above 5 m/s, the total convection losses increased linearly with wind speed. In addition, the wind speed presented here is the free stream wind speed measured at a fixed anemometer location a few metres from the dish. Wind direction also comes into play, especially the wind direction with respect to the dish (which will change due to dish tracking), because dish “shading” reduces the wind speed seen at the receiver aperture, compared to the free

Fig. 4. The solar dissociation experimental system and associated losses. The arrows pointing left from the system (red arrows) comprise the receiver losses – due to heat losses and reflection from the cavity. Accounting only for these losses gives the receiver efficiency. Adding these to the flux spillage, dish reflectivity, tracking error and heat exchanger losses gives the total losses in the system, which are accounted for in the solar-to-chemical efficiency.
Fig. 5. Receiver losses and total system losses with respect to solar altitude.

Fig. 6. Receiver losses and total system losses with respect to average tube temperature.

Fig. 7. Receiver losses and total system losses with respect to wind speed.
stream wind speed. This effect has been studied by Paitoonsurikarn [8, 9] using Fluent CFD modeling.

In Figures 5 to 7, total system losses are roughly double the receiver losses – total losses range from 5,500-6,500 W, while receiver losses range from 2,750 - 3,750 W; out of a total of 9,000 W incident on the dish. This large difference between receiver and total losses is in part due to the low reflectivity of the small dish mirrors (~77.5%), which have high iron content. However, this large difference illustrates that there is also significant room for reduction of losses from the heat exchanger and associated piping.

The receiver losses for the 3.7º half cone have shallower trendlines than those for total losses in the plots with respect to solar altitude and average tube temperature, but still with a positive slope. In the same plots, the receiver losses for the 7.5º half cone have a slightly steeper slope compared to the total loss curves, with the final slope being slightly negative. These changes in slope from receiver to total system losses simply illustrate that there are further temperature-dependent losses in the total system losses aside from the receiver loss component. These constitute the losses from the heat exchanger as well as from the piping between the reactor tube exit and the heat exchanger. As shown in Figure 8, due to setting a constant mass flow rate during the experiments, solar altitude was linearly proportional to average tube temperature – hence the change in slope in plots against solar altitude as well.

The differing slopes for the receiver losses between each of the three receiver geometries in Figures 5 and 6 indicate that differing heat loss mechanisms are dominating. The slight positive slope of the receiver losses for the 3.7º half cone with increasing altitude and temperature indicate that radiation (and possibly conduction) losses are dominating over convection losses. A cavity receiver should resemble a black body – i.e. radiation bounces around and is absorbed inside the cavity rather than being lost through the relatively small aperture, thus minimising radiation losses. However, with such a small half cone angle, the 3.7º half cone reactor tube bundle does not resemble a black body, and the tubes are more exposed to the aperture. In addition, Figure 13 shows that incident concentrated solar flux profile on the reactor tubes in this configuration (approximated by the cylinder with radius 77 mm) is highest closest to the aperture. This leads to the highest temperatures along the reactor tube being closest to aperture – as illustrated in Figure 12 and exacerbates radiation losses as the highest temperature sections of the tubes are most exposed to the aperture.

In contrast, the slight and steep negative slopes of the 7.5º half cone and 17.5º half cone in Figures 5 and 6 indicate that natural convection losses are the dominant heat loss from the receiver in these configurations. At higher solar altitudes, the receiver is more inverted, leading to lower natural convection losses. This decline in natural convection losses is in direct competition with increasing radiation and conduction losses at higher temperatures (corresponding to higher altitudes in these experiments, as per Figure 8). Thus on a preliminary analysis, it would appear that convection losses dominate the total receiver heat losses for the 7.5º half cone, and to a greater extent for the 17.5º half cone.

A more detailed analysis of radiation, convection and conduction losses is given in Section 4 for the receiver with 17.5º half cone angle.
3. Reactor Tube Temperature Profiles

During experiments, thermocouples recorded a temperature profile along one of the reactor tubes (tube 7), as well as a temperature reading for each of the other 19 tubes, from location B (approximately 20 cm) along their length, as illustrated in Figure 9.

Temperature profiles along reactor tube 7 are shown for all three receiver geometries in Figures 10 to 12. The profiles for the receiver geometries with 17.5º and 7.5º half cone angles (Figures 10 and 11) all fit to cubic polynomial trendlines, with the lowest temperatures closest to the aperture, a maximum around 20 cm, and a decline in temperature towards the back of the receiver. In addition to indicating heat transfer processes at the outer tube wall, the reactor tube temperature profile also indicates the extent of the thermochemical process occurring with the dissociation of ammonia within the reactor tube. For example, the drop in temperature after 20 cm in Figures 10 and 11 indicates that the endothermic reaction is dominating the temperature profile. Otherwise you would expect the tube temperature to continue rising towards the rear of the receiver as here the tubes are less exposed to radiation and convection losses through the aperture. While the concentrated solar flux profile also drops slowly after this point for both the 7.5º and 17.5º geometry (Figure 13), the flux input is still significant. The much steeper decline in temperatures after 20 cm for the 7.5º half cone (68ºC drop for 55.3º altitude in Figure 11, left) compared to the 17.5º half cone (45ºC drop for 55.2º altitude in Figure 10, right) is also a thermochemical marker. This indicates that the endothermic dissociation reaction is occurring at higher rate for the 7.5º half cone than the 17.5º geometry – which is confirmed by the higher efficiencies for the 7.5º geometry [1].

The temperature profiles for the receiver with 3.7º half cone angle are on the other hand approximately linear, with the highest temperatures reached nearest the aperture. This can be explained again with reference to the average flux profiles for the reactor tubes, as shown in Figure 13. In the 3.7º half cone geometry, approximated by the cylinder with radius 77 mm, the reactor tubes receive the peak concentrated solar radiation immediately from the very beginning of the reactor tube. Therefore it is logical that the highest temperatures for this receiver geometry are near the aperture. This temperature profile, along with the receiver geometry itself, contributes to the dominance of radiation losses for this receiver configuration.

In contrast, again with reference to Figure 13, the reactor tubes for the 7.5º and 17.5º half cone receiver geometries are not exposed to the concentrated solar radiation until a few, or several centimetres along the tube respectively. And still then it is several centimetres more before the peak flux arrives. These solar flux profiles explain why the temperature profiles for the 7.5º and 17.5º geometries begin at a minimum
temperature at 0 cm, and rise slowly to a maximum temperature between 15 and 20 cm. The difference in flux profiles for these two geometries compared to the 3.7° half cone geometry also explains why the 3.7° half cone geometry has higher initial temps – compare the temperature at 0 cm for solar altitudes of 35.5° (Figure 10, left), 36.9° (Figure 11, left), and 36.2° (Figure 12, left).

Fig. 10. Reactor tube temperature profiles for the 17.5° half cone receiver at selected solar altitudes. The distance 0 cm is closest to the receiver aperture. Left: 10th Feb, 1.25 g/s. Right: 29th Jan, 1.0 g/s.

Fig. 11. Reactor tube temperature profiles for the 7.5° half cone receiver at selected solar altitudes. 0 cm is closest to the receiver aperture. Left: 16th & 26th Mar, 1.25 g/s. Right: 16th Mar, 0.75 g/s.

Fig. 12. Reactor tube temperature profiles for the 3.7° half cone receiver at selected solar altitudes. 0 cm is closest to the receiver aperture. Left: 30th Apr, 1.5 g/s. Right: 14th May, 1.5 g/s.
Fig. 13. Average reactor tube flux profiles obtained by ray-tracing with OptiCAD. The 3.7º half cone is approximated by the 77 mm radius cylinder with light blue crosses.

4. Computed Losses

Figure 14 shows calculated receiver losses compared to those measured experimentally for an experiment with the 17.5º half cone geometry. The geometry used for all calculations was a simple frustum model of the cavity receiver divided into seven sections. Natural convection losses were computed given the tube temperature profiles and solar altitudes (which determine receiver inclination) from the experiment. These calculations were based on the CFD simulation results compiled by Paitoonsurikarn [9, 10] for the 9 m² dish cavity receiver. Natural convection losses decrease with solar altitude due to trapping of more hot air as the receiver becomes more inverted.

Radiation losses were calculated using a 7-node radiation network derived from the seven-section cavity, and view factors. The radiation losses increase in a linear fashion with solar altitude, due to the increased cavity temperatures with increasing altitude caused by operating at a fixed mass flow rate, as per Figure 8.

Conduction losses are approximately constant with altitude, but manifest a marginal increase with altitude, due to the increase in cavity temperatures with altitude in the constant mass flow experiments presented in this paper. Reflection losses from the cavity were calculated using first order reflections with view factors. These are minimal compared to the total receiver losses.

Comparing the dark blue diamonds to the grey triangles in Figure 14, we see that considering the simple models used for radiation and conduction losses, the agreement between calculated and experimental losses is satisfactory at high solar altitudes. The calculated losses under-estimate the experimental losses by 11-13% above 50º solar altitude. This discrepancy would be slightly reduced with the addition of forced convection loss estimates. However at low solar altitudes (below 50º), the under-estimation is more significant – up to 24%. This could indicate that the CFD simulations need to be re-visited with a more detailed receiver model. Alternatively, it could be due to an imperfect experimental factor such as an imperfect seal between the receiver casing and shield (the junction between the red and green sections in the cross section in Figure 9).
5. Conclusions and Future Work

Preliminary analysis of losses from the receiver indicate that as the half cone angle of the receiver tube frustum reduces – from 17.5° to 7.5° to 3.7° – we see a shift from convection-dominated losses to radiation-dominated losses. Reactor tube temperature profiles are a further indication of the heat transfer and thermochemical processes. Work is ongoing to compute losses for the 7.5° and 3.7° half cone receiver configurations. More accurate radiation calculations will be possible using view factors calculated with a more complex model of the cavity and reactor tubes using View3D software [11].

References


