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Thermal performance of a solar oven with augmented sunlight concentration

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Abstract

This paper describes the thermal performance of a novel solar oven that incorporates a compact reflective lens, or ring array, to augment sunlight concentration. Performance is reported in terms of the positive effect of the ring array versus a non-concentrating lid, maximum operating temperature, thermal efficiency, performance under partly cloudy skies, and the effects of incidence angle and tracking. Use of the ring array lens improved thermal efficiency by 4% in the test range up to 100°C, while boosting the maximum operating temperature from 138°C to 196°C. Comparative tests conducted under clear sky conditions against two other commercial types showed that when tracked in the azimuth plane at near-normal incidence angles, the new design generated maximum cooking power of 300 W and boiled water at a rate 13% faster than the next best commercial oven tested. Augmented sunlight concentration sensitised the new design to higher angles of incidence and performance was negatively affected in the non-tracked state. Under non-ideal operating conditions, including partial shading by cloud, the oven outperformed both commercial units.

Keywords: solar oven, ring array concentrator, thermal efficiency, solar irradiance

Introduction

Solar ovens collect and retain heat from the sun to provide a safe and environmentally clean method of cooking food and sterilising water. In particular, the technology has strong potential for use by residents of non-electrified settlements, as has been shown in developing countries such as India. Unequal access to safe energy sources in South Africa would suggest similar potential for widespread deployment. As the University of Cape Town's Energy Research Centre notes, the use of wood and paraffin carries health risks for people in informal settlements (Winkler et al 2005). Apart from the danger of runaway fires, smoke in poorly ventilated dwellings causes respiratory disease and contributes to the infant mortality rate. Additionally, damage is caused to the environment as firewood is depleted.

Matzopoulos et al (2006) highlighted a further danger related to domestic energy use in this country, namely significant levels of paraffin ingestion by children. Given that an estimated 3.5 million South African households were not electrified by 2002 (Prasad and Visagie 2005), the use of solar ovens should be widespread, yet this is not the case. Research suggests complex reasons, including poor equipment performance and lack of acceptance arising from social, economic and cultural factors.

Wilson and Green (2000) studied solar oven deployment in a rural KwaZulu-Natal community and found the benefits of avoiding arduous wood collection were enough to induce acceptance of the technology by inhabitants. However, commercially available solar ovens were found to have limitations such as insufficient capacity for the average number of inhabitants per household, inadequate maximum operating temperatures which limited the types of food that could be prepared, and an inability to provide cooking heat in the evening. Clearly, better solar ovens are needed.

This study extends earlier work by the author to develop a prototype oven using augmented concentration of incoming solar radiation to boost thermal performance, especially maximum operating temperature (Brooks 2006). Further experimental results are presented and selected data from a preliminary study are included to provide a comprehensive picture of performance.

Equipment design and construction

Most solar cookers are of the oven-type and work by trapping heat in an enclosed, insulated space. Although some designs incorporate a degree of sunlight-concentration through reflective internal walls or externally deployed panels, concentration ratios are generally low. Higher temperatures may be obtained using parabolic concentrators, where the exposed cooking container is placed at the focal point. This approach requires constant, accurate tracking and lacks the convenience of an oven space. The oven described here, called a ring array concentrator oven, or 'RACStove' for short, is a hybrid in that it possesses both a conventional oven space and a meaningful concentration ratio. As with conventional units, the RACStove traps solar energy in its enclosed space using the greenhouse principle. Additionally, the ring array's concentrating ability is exploited to focus solar energy on an aluminium base plate, heating the cooking container by conduction from beneath to temperatures greater than would be possible without augmented concentration.

Key to RACStove operation is the oven lid, consisting of a transparent disc supporting a modified reflective lens, or ring array concentrator, based on the concept proposed by Vasylyev and Vasylyev (2005). Unlike the original concept, the concentrator used here consists of a nested set of 15 reflective rings flattened to facilitate integration with the oven structure and provide a compact shape. The mirror elements are straight conical sections angled and positioned to avoid blockage of reflected light by adjacent mirror elements. Figure 1 illustrates the concentrating effect of the ring array for the general case where the oven lid is positioned horizontally.

The reflective surfaces of the ring array concentrate 54% of direct beam irradiance that falls on the RACStove's circular lid, with the remaining energy passing through to irradiate the cooking container directly, or striking the inclined sides of the cone to be directed towards the base. The central, non-focusing part of the oven lid was retained to desensitise the unit to tracking inaccuracies, daily and seasonal variations in incidence angle and a reduction in beam irradiance in the presence of cloud. The theoretical concentration ratio for the ring array used in this study when positioned horizontally as in Figure 1 is 29.3. For this study, the lid was angled 25° to the horizontal to account for the geographic location of the test facility (Figure 2). At this angle, the adjusted concentration ratio is approximately 26.6. In practice, a further reduction occurs because of inaccuracies in the manufacture of the ring array, imperfect specular reflectance of the aluminium and alignment errors which lead to defocusing of the light ring.

The prototype RACStove shell was constructed commercially from glass-fibre and a high-temperature resin system. The ring array was fabricated from 0.4 mm gauge Miro 4 aluminium with ρ = 0.95. Two lids were manufactured for the oven, one bearing the ring array and a second made of plain glass to allow for testing to isolate the effect on performance of the oven shell from that of the ring array. Each lid consisted of a 4 mm thick tempered glass disc (D = 1040 mm, τ = 0.81, A_{int} = 0.79 m^2).

Experimental results and discussion

Since the prototype is new in both its overall design and its use of a ring array concentrator, testing was conducted to characterise performance in four

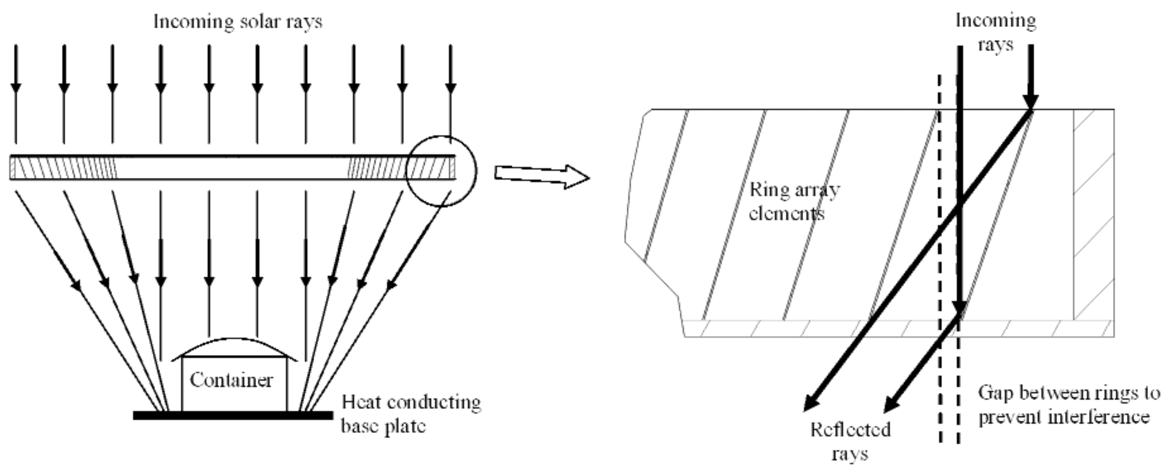
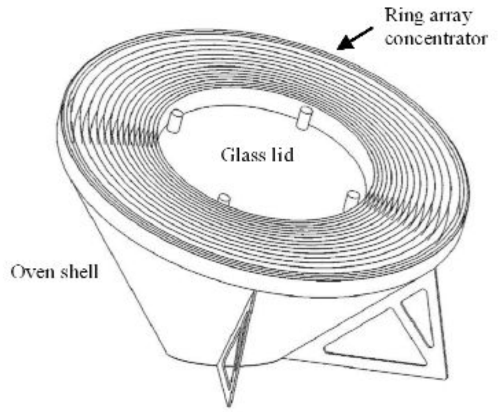
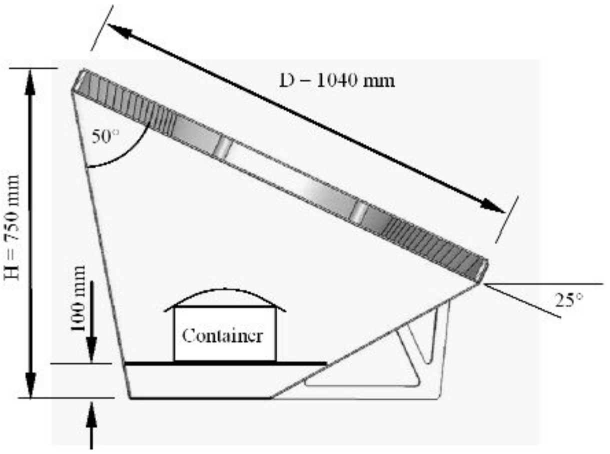


Figure 1: Schematic of RACStove operation for a horizontally-aligned ring array with concentrated sunlight focused on oven base plate (left), and detail of reflected solar ray path between mirror elements (right)



(a)



(b)

Figure 2: a) Conical RACStove shell incorporating lid with ring array; and b) internal arrangement with key dimensions

respects: performance with and without the ring array, performance as a function of solar incidence angle, comparative clear-sky performance of the RACStove versus two commercial ovens and comparative performance under partly cloudy skies. With the exception of the last category, all tests were conducted under clear sky conditions. The method used loosely followed that proposed by Funk (1997), in which the oven is loaded with water in proportion to its intercept area and the temperature rise measured over time. This determines behaviour in the standard range up to 100°C. Water is replaced with vegetable oil to find the maximum operating temperature. For comparison, two commercially available solar ovens ('C1' and 'C2') were tested alongside the new design. Oven C1 is the more expensive of the two and deploys a set of external mirrors to increase its intercept area ($A_{int} \approx 0.54$ m^2, water loading = 2.05 kg). Oven C2 consists of a simple plastic shell and reflective internal walls fabricated from used aluminium printing plates ($A_{int} \approx 0.35$ m^2, water loading = 1.34 kg). Both ovens are single-glazed and their inclusion in the test program provided a useful opportunity to benchmark RACStove performance. Figure 3 shows a comparative test in progress at Mangosuthu Technikon's Solar Thermal Applications Research Laboratory (STARlab) (29° 58.214' S, 30° 54.901' E).

Figure 3: Clear-sky performance tests, with (left to right) the RACStove and ovens C1 and C2

Effect of the ring array concentrator

To determine the effect of the ring array, tests were run first with the lid incorporating the concentrating lens ('RACStove' in the graphs) and then with the RACStove minus the ring array (designated 'RACStove (-RA)'). These took place under similar clear-sky conditions and at angles of incidence (θ) close to the average experienced during the test programme (10°). Using water as the working fluid, results were obtained by measuring the temperature rise of the oven load over successive 2 minute intervals while tracking in the azimuth plane. Point efficiencies were calculated as the ratio of developed power or rate of energy transfer to the working fluid, to the rate of solar energy incident on the oven lid for each interval *i*:

$$\eta_i = P_{dev,i} / P_{avail,i} \quad (1)$$

where: $$P_{dev,i} = m\, c_p\, \Delta T_{int,i} / 120 \quad (2)$$

$$P_{avail,i} = G_{DN,i}\, A_{int} \quad (3)$$

Efficiency is shown in Figure 4 as a function of temperature difference between the oven contents and ambient. The negative gradients indicate heat loss and are similar in magnitude for both curves, which was expected given that the same oven shell was used. The effect of the concentrating lens was to increase efficiency by an average of 4% over the boiling range. This was achieved without altering the interior of the oven or increasing its intercept area.

Water was replaced with oil to determine the effect of augmented concentration on the maximum operating temperature of the oven (Figure 5). Tests were conducted on different days, but under similar radiometric and incidence angle conditions. With the array fitted the initial time response was

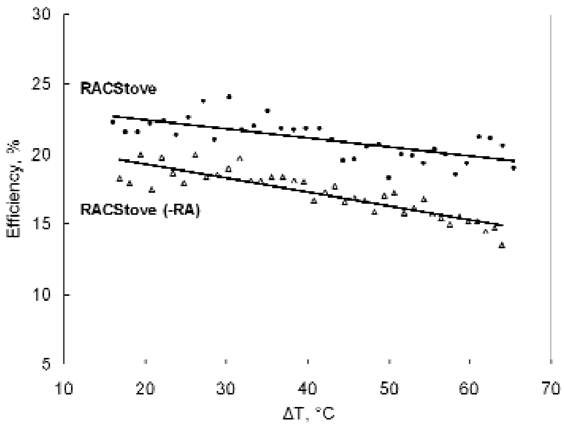


Figure 4: Effect of the ring array concentrator on thermal efficiency in the standard testing range with water as the working fluid

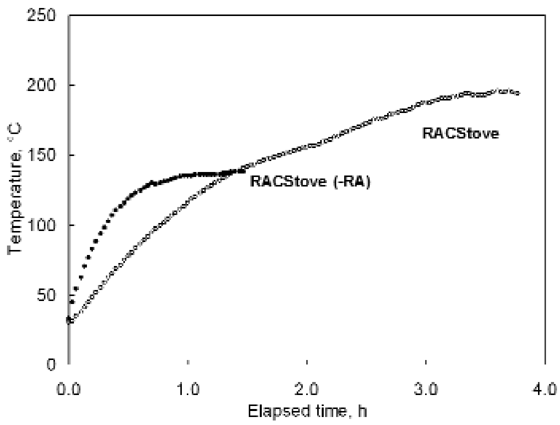


Figure 5: Maximum temperature results for the RACStove with and without augmented concentration using oil as the working fluid

slower, probably because of greater sensitivity to non-normal incidence. Overall, maximum temperature was boosted by 42% with the RACStove reaching a peak temperature of 138°C without the ring array and 196°C with augmented concentration in place.

Effect of incidence angle (θ)

Sensitivity to increased angles of incidence was determined by running water-based tests under clear-sky conditions at times of the day when the average value of θ was 21°, 11° and close to zero. Results are shown in Figure 6. Since the tests lasted from one to three hours, some variation in θ relative to the averages was allowed. Variation in the average irradiance between the three tests was less than 4%. The penalty for operating the oven at higher incidence angles is clear. For extreme values of θ, the best fit curve suggests that performance would level off at an approximate minimum of 100 W, corresponding with the oven being driven mostly by energy admitted through the non-concentrating central portion of the lid. Figure 6 projects a maximum of approximately 300 W at zero incidence, a value close to maximum experimental results recorded during the study.

Performance relative to commercial units

In runoff tests against ovens C1 and C2, the new design performed well. With regular tracking of all the units at 10 minute intervals and for near-normal conditions, the RACStove reached boiling point in 66 minutes, 10 minutes or 13% faster than C1 (Figure 7). The best fit curves in Figure 8 give maximum projected thermal efficiencies of 40% for the prototype oven, 38% for C1 and 28% for C2. Under almost identical irradiance with θ = 21°, C1 performed best, boiling water in 150 minutes, 20 minutes or 12% faster than the RACStove (Figure 9). Again, this illustrated the sensitivity of the new design to non-normal incidence. At both high and low incidence angles the prototype outperformed

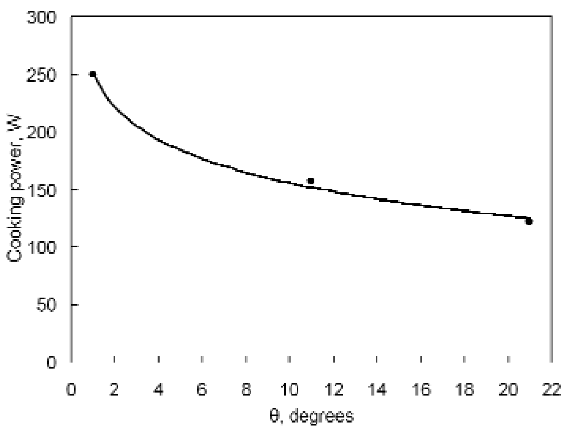


Figure 6: Average cooking power as a function of incidence angle for water-based tests (Brooks, 2006)

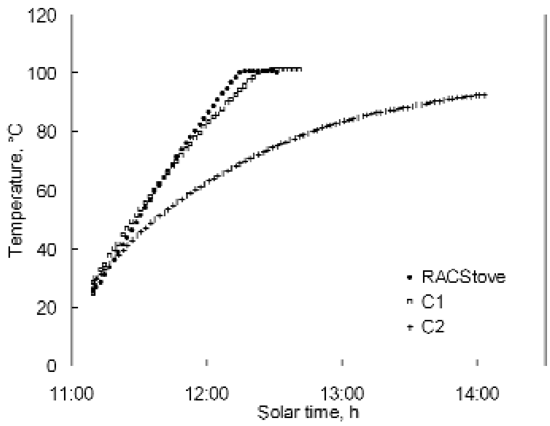


Figure 7: Performance for near-normal incidence conditions with tracking and averaged irradiance G_{DN} = 903 W/m^2 (Brooks, 2006)

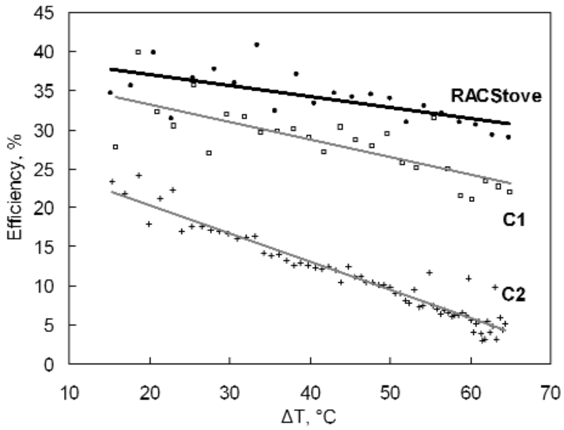


Figure 8: Efficiency for near-normal incidence conditions with tracking and averaged irradiance G_{DN} = 903 W/m^2

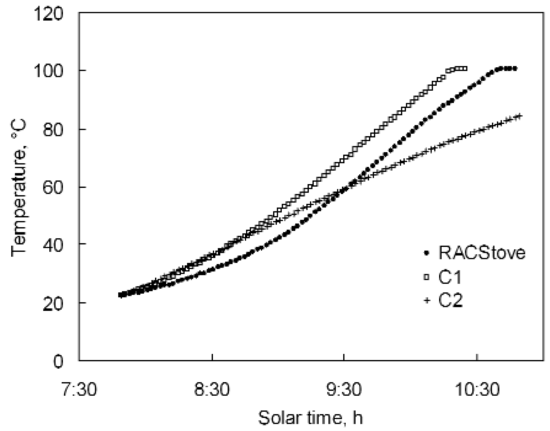


Figure 9: Performance for θ = 21°, with tracking and averaged irradiance G_{DN} = 896 W/m^2 (Brooks, 2006)

C2, which struggled to boil water in the time allotted for testing.

Pronounced non-linearity of the RACStove efficiency curve in Figure 10 is due to high incidence angles early in the test. As these declined, the heat loss effect once again dominated to produce a negative gradient consistent with normal solar collector behaviour. The non-linearity of C1's curve is slightly less pronounced because of its limited ability to concentrate sunlight with externally deployed mirrors. C2, which has almost no concentrating ability, is affected much less by changes in θ, however, these tests illustrate the price which it pays in overall performance. During oil-based tests, ovens C1 and C2 reached maximum operating temperatures of 175°C and 118°C respectively, both well below the maximum obtained under identical conditions with the RACStove.

Effect of tracking

The above results imply better high-temperature performance from solar ovens equipped with some kind of concentrating capability, however, this usually necessitates constant tracking of the device in the azimuth plane to minimise θ. The disadvantage of manual tracking is that it might be considered onerous by users and discourage adoption of solar cooker technology. To quantify the effect of tracking, the new design and both commercial ovens were oriented towards true north and left stationery for several hours starting at 09:30am (Figure 11). The lower graph gives G_{DN} and θ (calculated for the RACStove) for the test period, during which beam irradiance averaged 853 W/m^2. Oven C2 initially responded quickest, as seen by its steeper gradient. Again, this reflects a lack of concentrating mirrors desensitising the unit to higher values of θ. C2 failed to reach boiling point by the end of the test. Oven

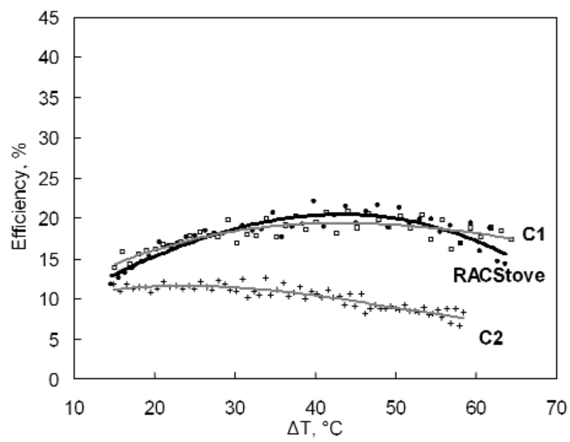


Figure 10: Efficiency for θ = 21°, with tracking and averaged irradiance G_{DN} = 896 W/m^2

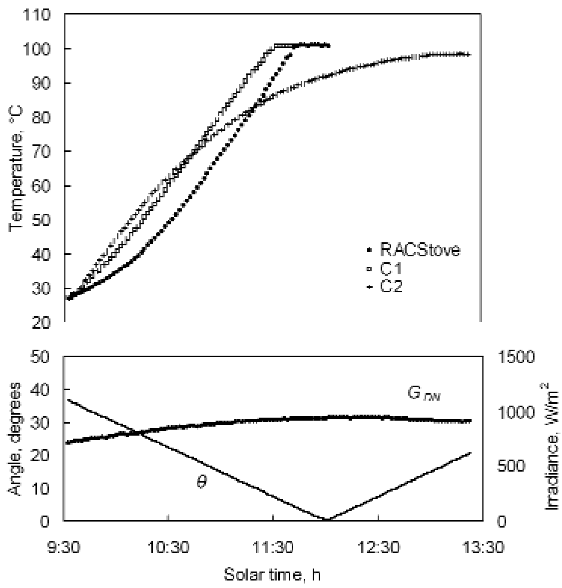


Figure 11: Performance for the stationery test (ovens facing true north), with lower graph indicating beam irradiance and solar angle of incidence for the prototype RACStove (Brooks, 2006)

C1 reached boiling point first in a time of 118 minutes, followed closely by the RACStove in 130 minutes, 10% slower.

The shallow gradient of the RACStove curve in the initial phase can be ascribed to greater oven mass which must heat up from a cold start, and increased sensitivity to higher angles of incidence. Encouragingly, these results suggested a relatively small penalty to be paid for stationery operation of the RACStove.

Performance in a typical duty cycle

Once deployed, solar ovens are likely to operate under conditions less ideal than those of the test environment – for example, clouds will shade the device intermittently and tracking may not be rigorously applied. To determine the effects of a typical duty cycle, the prototype RACStove and both commercial ovens were subject to a combination of varying solar irradiance and inaccurate tracking, the results of which are shown in Figure 12, along with total global irradiance in the horizontal plane.

During the periods marked A, B and C, changes in operating conditions were forced on the ovens. In period A, all three units were artificially shaded for 10 minutes, exposed for 10 minutes then shaded again for 13 minutes during period B. After this, the ovens were left exposed however, natural shading by cloud occurred intermittently after 11:30am, as shown by the irradiance plot in Figure 12. Between 11:50am and 12:30pm (period C), no tracking was applied. The step effect of turning the solar resource off and on can be seen in the temperature plots. Not surprisingly, RACStove performance suffered more than the commercial units towards the end of the non-tracking phase, yet of the three ovens tested, the new design was able to bring its water load to boiling point first. Although Figure 12 represents only one possible duty cycle, the results obtained show that an oven with augmented concentration can cope with a variable solar energy source.

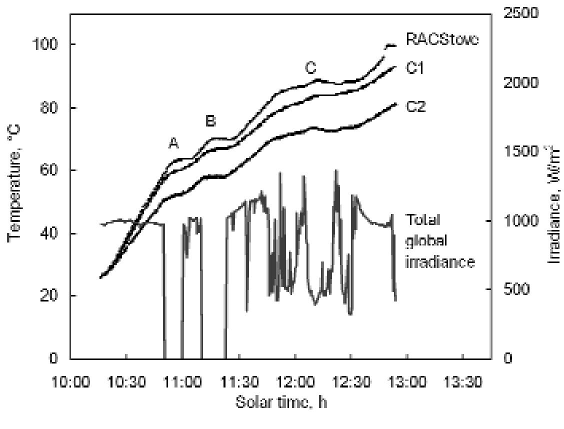


Figure 12: Comparative oven performance under a typical duty cycle comprising two periods of complete shading lasting 10 minutes and 13 minutes (A and B respectively) and an extended period of non-tracking combined with variable irradiance lasting 40 minutes (C)

Conclusion

Augmented sunlight concentration can improve thermal efficiency and substantially increase maximum operating temperature of a solar oven, without the need to increase the collector area or improve the oven's heat retention properties. This was demonstrated by building a compact ring array concentrator into a prototype oven, which was tested alongside commercial units.

Thermal performance compared favourably with the commercial ovens both under clear-sky conditions and a typical duty cycle with variable irradiance. A disadvantage is greater sensitivity to non-normal angles of incidence, necessitating some form of tracking, although this study shows that it is possible to balance high performance with less arduous tracking requirements by designing a hybrid oven with concentrating and non-concentrating features. Work remains to optimise the prototype, however, these results suggest that augmented concentration in solar ovens may help to eliminate the performance limitations identified by rural communities, bringing greater acceptance of the technology and its associated health and safety benefits.

Nomenclature

- A_{int} = intercept area, [m^2]
- c_p = specific heat capacity, [J/kgK]
- D = lid diameter, [m]
- G_{DN} = direct normal irradiance, [W/m^2]
- H = height of oven, [m]
- m = mass, [kg]
- P_{avail} = rate of direct solar irradiation, [W]
- P_{dev} = rate of energy transfer to cooking load, [W]
- T = temperature, [°C]
- ΔT = water temperature minus ambient temperature, [°C]
- ΔT_{int} = water temperature rise between successive measuring intervals, [°C]
- θ = angle of incidence between solar vector and normal to oven aperture, [deg]
- ρ = reflectance
- τ = transmittance

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References

Brooks, M. J. 2006. Application of a ring array concentrator in design of a solar oven. In Proceedings of the 4th International Energy Conversion Engineering Conference (IECEC), San Diego.

Funk, P. 1997. The international standard for testing solar cookers and reporting performance," In Proceedings of the Third World Conference on Solar Cooking, Coimbatore.

Matzopoulos, R., Jordaan, E. & Carolissen, G. 2006. Safety issues relating to paraffin usage in Eshane, KwaZulu-Natal. *Journal of Energy in Southern Africa* 17 (3): 4-9.

Prasad, G. & Visagie, E. 2005. Renewable energy technologies for poverty alleviation: Initial assessment report: South Africa. Energy Research Centre. University of Cape Town.

Vasylyev, S. & Vasylyev, V. 2005. Nonimaging reflective lenses: A new type of high-heat solar collector. In Proceedings of the Solar World Congress, Orlando.

Wilson, M. & Green, J. M. 2000. The feasibility of introducing solar ovens to rural women in Maphephethe. *Journal of Family Ecology and Consumer Sciences* 28: 54 - 61.

Winkler, H., Alfstad, T. & Howells, M. 2005. South African energy policies for sustainable development. Energy Research Centre. University of Cape Town.

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