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Continuous flow solar disinfection system for a rural community in Kenya

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This project involved the design and installation of a continuous flow solar disinfection reactor at a rural village of approximately 500 population in a drought prone part of Kenya. The system was installed to disinfect surface water collected at a recently constructed micro-dam. The solar reactor uses CPC reflectors which reflect both direct and diffuse solar radiation onto clear pipes through which the requisite water supply flows. The system has been installed to operate by gravity flow between the hours of 9am to 5pm. The community fully participated in the planning, installation and subsequent operation of the system. Preliminary water quality results indicate that the system is providing a safe source of water for the community. However, the technology needs to be evaluated over a longer period across a wide range water quality and solar radiation conditions, in particular during the next rainy season.

Background

One of the key targets of the Millennium Development Goals is to halve, by 2015, the proportion of people without sustainable access to safe drinking water. In developing countries water related diseases account for the majority of premature deaths which in many cases could be alleviated by the provision of an adequate supply of water for both drinking and washing (Cairncross and Feachem, 1993). In such situations there are often neither the finances nor the resources to construct and maintain the types of water treatment processes used in more industrialised countries which tend to be both energy and chemical intensive. This project involves the development of a process which uses solar radiation, an abundant resource in most developing countries, to disinfect water supplies. The germicidal effect of natural sunlight was first reported by Downes and Blunt (1877) and since then efforts have been made to harness the sun for disinfection purposes. Several investigators around the world have carried out studies on the solar disinfection of a variety of different micro-organisms (bacteria, protozoa and viruses) under either solar simulator lamps or out in real sunlight (Sommer et al., 1997; Smith et al. 2000; Vidal and Diaz, 2000; Reed, 2004; Méndez-Hermida et al. 2005). A comparison of the effectiveness of solar (or photolytic) disinfection against different target organisms has recently been summarised by Gill and McLoughlin (2007).

The enhancement of the solar disinfection process by photocatalytic oxidation has also been demonstrated with continuing research proving successful against a range of micro-organisms (Salih, 2002; Ibáñez et al. 2003). Such studies have mainly used titanium dioxide (TiO2) in a suspended form as the photocatalyst due to its effectiveness against a range of both natural and synthetic organics (Robert and Malato, 2002). However, the use of photocatalytic suspensions is not considered to be a particularly attractive solution for a small-sale rural water supply system since the TiO2 will require some form of separation and recovery process at the end of the solar reactor before the water is suitable for consumption. Hence, a fixed catalyst needs to be developed if the technique is going to be applicable for such an application. One of the potential benefits of using a photocatalyst reported by some authors is that the photocatalytic disinfection mechanism prevents any re-growth of the micro-organism post-irradiation if the water is subsequently stored in the dark (Rincón and Pulgarin, 2004a, b). Solar (or photolytic) disinfection however, has also been found to have a sub-lethal, as well as a lethal effect, whereby membrane damage leads to bacterial growth delay after irradiation (Berney et al. 2006). The synergistic effect of solar UV and raised water temperature has also been investigated (Safapour and Metcalf, 1999; Gill and McLoughlin, 2007)) revealing a clear advantage of increasing temperature to at least 45ºC in order to enhance the solar disinfection process.

Research carried out in recent years has focused on batch systems involving the storage of small quantities of water (up to 1 litre) in transparent vessels, either bottles or bags, and exposing them to sunlight for periods of up to eight hours (McGuigan et al. 1999; Smith et al. 2000; Walker et al. 2004; Lonen et al. 2005). Whilst, studies have also shown the effectiveness of this batch process in field trials (Conroy et al. 1996; Sommer et al., 1997), the volume of water disinfected in each bottle is limited and depends upon the dedication of each user. Such disadvantages are not of concern for centralised continuous flow systems. To date, the majority of work using continuous flow solar systems has concentrated on detoxification of water contaminated with chemical compounds (Malato et al. 2002) with little research carried out in the field on the solar disinfection process. The pilot and laboratory scale studies that have been carried out using solar reactors have proved successful against bacteria (Acra et al. 1989; Vidal and Diaz 2000; McLoughlin et al. 2004a, b; Rincon and Pulgarin 2004) and indicate that continuous flow solar disinfection is a promising alternative to conventional disinfection techniques for use at a village scale.

Continuous flow systems have been studied extensively by the research team under artificial lamps in the laboratory and out in Irish sunshine (McLoughlin et al., 2004a), and then in full-scale experimental prototypes in Spain (Mcloughlin et al., 2004b). Although research in laboratories around the world continues to look at the inactivation of ever more diverse pathogenic species and enhancements to the basic photolytic process, the basic principle of solar disinfection has been proved and there is a pressing need to install and evaluate such continuous flow technology under real conditions, both from the point of view of disinfection efficiency but more crucially perhaps, from the local acceptability, operability and maintenance perspective of the communities targeted. The aim of this project was thus to install a system in a rural village in sub-Saharan Africa.

The project was carried out in collaboration with the Irish International Humanitarian Organisation, GOAL which currently works in 9 sub-Saharan countries with a significant water and sanitation focus to their activities. After negotiation it was decided that the Mutomo District in Kenya would be the most suitable area to host the system due to a previous intervention by GOAL in the region in collaboration with the Diocese of Kitui. The project was to undertake Emergency Water Provision for Drought and Famine affected populations which lead to the construction of several sand storage dams for individual village water supply. The sand storage dams fill from surface runoff during the rainy season and so can not be regarded as a protected source. Hence, ideally the installation of a disinfection system of the water prior to consumption is required.

System design

Continuous flow solar disinfection principle

The principle behind the continuous flow disinfection system is shown on Figure 1.

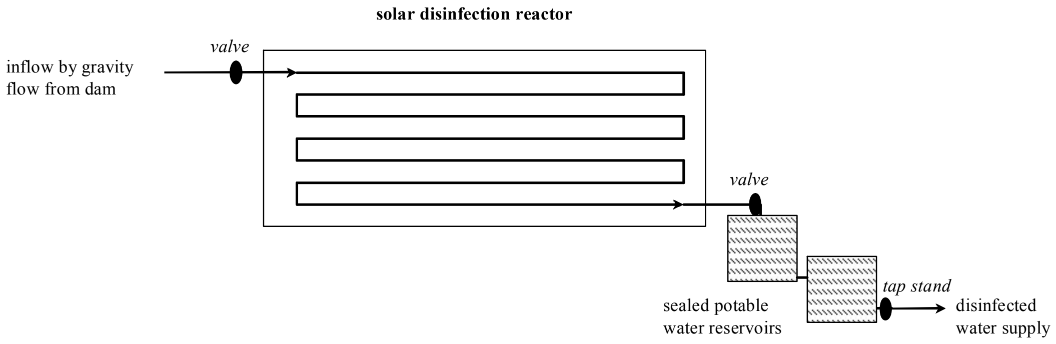

Figure 1. Schematic diagram of solar disinfection system

Water moves by gravity from the sand storage dam through the reactor (in which it receives the requisite dose of solar UV to inactivate any pathogenic organisms) before discharging into two storage reservoirs in series. The flow rate through the reactor is controlled by an outlet valve to ensure the water receives the correct cumulative sunlight dose for complete disinfection. The water storage tanks are designed as a buffer between the continuous water supply during the daytime and erratic water demand from the local population. The storage tanks also allows people to collect water either early in the morning or later in the evening (as is normally the local custom) when the heat of the day is less which is obviously not compatible with the hours of operation of the solar disinfection system, which can only operate during daylight hours.

Reactor sizing

In order to design a continuous flow solar disinfection reactor some form of decay coefficient needs to be established for the proposed system. The definition of the decay coefficients used by different groups involved in solar disinfection research varies and no single standard has apparently been adopted. Classical disinfection kinetics (used for chlorination, UV mercury lamps etc) predict a first order linear decay with respect to time as described by Chick's Law (Chick, 1908) (Eq. 1).

$$\frac{dN}{dt} = -kN \rightarrow N_t = N_0 e^{-kt} \qquad (1)$$

where, N_t is the number of viable organisms at time, t; k is the inactivation rate constant.

Hence, many studies report the logarithmic reduction in viable organisms over time, which is fine for studies where one microorganism is being directly compared with another under identical conditions (for example, under a solar simulator at a fixed intensity) but starts to loose any useful interpretation if used in real sunlight since it does not distinguish between experiments carried out under varying solar intensities at different times of the day, year or weather conditions. Hence, for trials carried out in real sunlight conditions it is more appropriate to define the disinfection kinetic based upon the cumulative UV dose received (Q_{UV}) as shown in Eqs. 2 and 3.

$$\frac{dN}{dt} = -kN \rightarrow N_t = N_0 e^{-kQ_{UV}} \qquad (2)$$

where, Q_{UV} is defined according to the cumulative Eq. 3. [6].

$$Q_{uv,n} = Q_{uv,n-1} + \frac{\Delta t_n UV_{G,n} A}{V_T} \qquad (3)$$

where Q_{UVn}, Q_{UVn-1} is the cumulative irradiated UV energy received per litre of sample at times *n* and *n*-1; Δt_n the time interval between sampling times; UV_{GN} the average incident radiation on the irradiated area; A the irradiated area; V_T the total circulating volume.

The continuous flow of water in a glass pipe was designed to flow through non-tracking Compound Parabolic Collectors (CPC). These are static collectors with a reflective surface following an involute around a cylindrical reactor tube (see Figure 2) and are a cross between trough concentrators and non-concentrating, one-sun systems meaning that both direct and diffuse UV radiation arriving at the aperture area are available for the process in the reactor. Any UV radiation reflected by the CPC is distributed around the back of the photoreactor and as a result most of the reactor tube circumference is illuminated. When designed with a concentration ratio of one they have both the advantages of parabolic trough collectors and one-sun designs. Hence, its performance has been shown to be very close to that of the simple tubular photoreactor, whilst only requiring about one third of the reactor tube material. The reactor used was fabricated in Portugal by AoSol to the same specification as the reactors used by the research team in previous studies carried out in the Plataforma Solar de Almeria in Spain (Mcloughlin et al., 2004b). The CPC profile, shown on Figure 2 had a half acceptance angle of 90^0 aperture width of 94 mm and internal pipe diameter of 47.2 mm. The pipes were made from Pyrex which has a low iron content to ensure the maximum transmissivity to sunlight in the UV spectrum. The manufacturer supplied the reactors in compact panels of 10 parallel pipes (see Figure 3), each of 1.5 m in length.

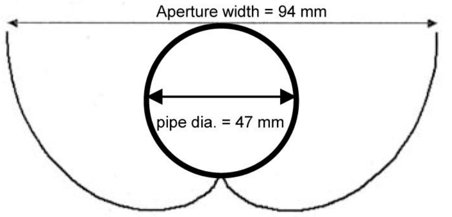

Figure 2. CPC reflector profile

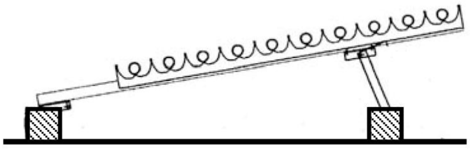

Figure 3. cross-section of solar reactor

Initially, a target village population of 500 people was assumed for the preliminary design. A realistic water consumption figure of 10 litres per person per day for drinking, cooking and personal hygiene was taken on the basis of previous surveys in the region. This yielded a total water flow required of 5000 litres per day. The system design was then based upon a threshold solar UV intensity of 25 W/m^2 which would typically be met or exceeded for at least 8 hours every day (i.e. 9am and 5pm) at such a latitude which would be the hours of operation of the system. From this, the mean continuous flow rate during operating hours was calculated to be 10.4 litres / min. The next step was to calculate the length of reactor needed which dictates the amount of time the water (and any pathogenic micro-organisms) experiences sunlight at, or above, the threshold UV intensity. The microbiological quality of the water taken directly from the dam was not known and so a conservative value of 10^5 *E. coli* / 100ml was assumed – which would be indicative of very poor water quality. An inactivation constant (k) of 1.7 litres / kJ$_{UV}$ was used for the design on the basis of previous work on a similar reactor in Spain using the thermotolerant coliform bacteria *E. coli*. Using the collector area receiving the threshold UV intensity and the mean flow rate, a total length of reactor pipe of 128 m was then calculated in order to achieve complete disinfection, equating to 8.6 panels. This design was felt to be over conservative due to the fact that for most of the day the UV intensity is way above the threshold (see later) and so a total of 8 panels (120 m of reactor pipe) were fabricated for the system for transport to Kenya. At the design flow rate the water (and any pathogenic micro-organisms) would therefore spend approximately 20 minutes in the reactor environment, assuming plug flow conditions.

System installation

Site conditions

The village chosen for the installation of the solar disinfection system was Ndulyani in the Mutomo District of Eastern Province in Kenya. As discussed previously, GOAL had recently been working with the community to construct a sand storage micro-dam. The community had been well motivated during the previous project and the population size was suitable (around 500 people) for the solar disinfection system design. The sand storage dam also provided a reliable source of water to flow through the reactor, water which was currently an open source (and thus at risk of pollution) as the sand had yet to accumulate behind the structure. The principle of the sand storage dam compared to an open water dam is that has the advantage of reducing evaporative losses and also providing some form of protection to the water resource from pollution.

As the dam had only been constructed after the main long rainy season (late November to early December) in the previous year it had not yet filled to capacity, as shown in Photograph 1. The intended full depth of water 2.3 m at the dam wall which decreases at a constant gradient moving back up the valley to a flooded surface length of 650 m and mean width 19 m. In time the accumulated sand will obviously take up some much of the volume, so assuming a porosity of 30% (crudely calculated on site using a bucket and representative sediment) this should leave a total volume of water following each rainy season of 4.3 megalitres. This water should then last for the next 8 months until the next rains occur in July which, taking into account evaporative losses will equates to an average water resource available of over 30 litres per capita per day for the local community.

The diurnal solar UV intensities were measured at the site over a number days (see Figure 4) using a PMA2100 radiometer (Solarlight, USA) which confirmed that the UV light intensities at 9am and 5pm were in or around the assumed design intensity of 25 W/m^2 Heavy cloud in the morning of 31st August showing decreased UV intensities. However, it must be borne in mind that even if the system starts operation at a time where the intensities are slightly lower than the threshold value, the influent water will then spend almost 20 minutes in the reactor before exiting to the storage tanks during which time the solar intensities will have risen steeply.

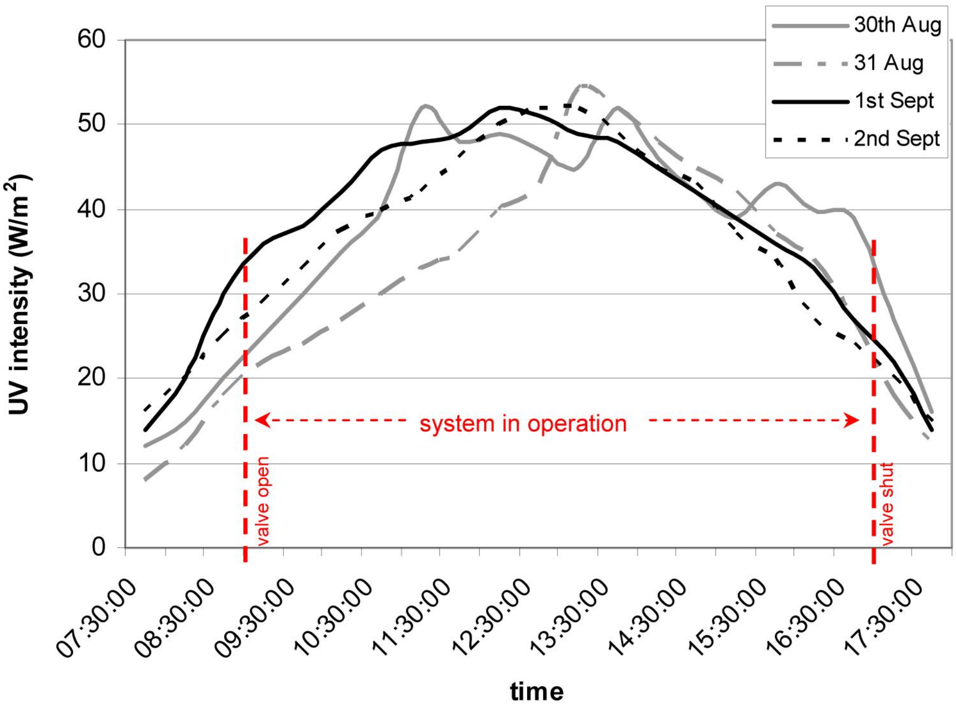

Figure 4. Diurnal UV solar intensities measured at Ndulyani village

Community mobilisation

It was essential to gain full cooperation from the local community and engage them fully in the project installation if the system was to be sustainable. A local community meeting (*Baraaza*) was called to communicate the aims of the project and hear the expectations from the community. The GOAL community mobiliser and WASH coordinator provided an essential input at this stage with respect to the community involvement. The WASH team continued with a programme of sanitation and hygiene education which highlighted the benefit of the system with respect preventing common water associated illnesses. A formal community agreement was drawn up whereby the roles of GOAL, the contractor and the community were clearly defined. The community made the agreement to supply preliminary works (site clearance, supply of local materials and provision of non-skilled labour) and then the final operation and maintenance of the system. The WASH coordinator also helped to establish a Water Committee which had equal gender representation of two males and two females. It was also particularly heartening to witness the interest shown and involvement by the high numbers of women who turned every day to help during the installation of the system. A Community Land agreement was also drawn up between GOAL, the land owner, village chief and committee members and Kitui District Administrative Office.

Finally, it was also necessary to gain a Kenyan research permit. This was sought and approval was granted following meetings with the Ministry of Water and Irrigation. It was also essential to keep the District Water Office informed and involved at all stages of the project.

Construction

The construction was programmed to take place during the dry season. A local contractor was appointed on the basis of having previously worked with GOAL in the area. The local topography of the land below the micro-dam was ideal for the flow of water by gravity through the system located on the river bank at a site

30 m away. A calculation of the head losses required to create a flow of 10.4 L / min from the dam through 50 mm galvanised iron pipe and then through the glass tubes in system with respective minor losses for bends and valves returns a value of less than 0.1 m. The final difference in head levels across system from low water level in the dam to the outlet of the system was in excess of 1 m, meaning that the natural gravity flows would have to be restricted to the design flow using a valve.

A level area (30 m^2 plan area) was cut into the bank requiring 16 m^3 of soil removal and was stabilised by gabions in the form of a retaining wall to reduce risk of land slippage, particularly during the rainy season. The area was aligned in an east-west orientation to optimise the solar gain of the photo reactor which does not track the sun. The site was located as high as possible above the river bed to avoid the risk of flash flooding but low enough to attain a reasonable head across the system to allow gravity flow at all times. The foundation of the system was prepared by constructing strip foundations upon which to install the solar disinfection system as can be seen in Photograph 2. The system frame was cast into the foundation and the reflectors bolted onto the frame. In the end it was decided to install 7 panels in series due to the higher influent water quality than expected. The reason for this was to leave the community with one extra panel (and 10 spare tubes) for future maintenance. However, in the future the extra panel can easily be added if required to improve the disinfection performance.

Photograph 1. partly full dam

Photograph 2. solar disinfection system installation almost complete

An intake filter was installed behind the dam on the basis of a well screen technique whereby the pipe was extended upstream into the dam and a 100 mm uPVC pipe was placed on the 50 mm galvanised iron pipe. The plastic pipe was then slotted and covered with fine plastic gauze. The pipe was inverted to 0.45 m above the base of the dam to prevent blockage. The intake filter was then protected with a gravel filled gabion formed of increasingly fine grains from the outside in to the filter pipe. The connection through the 0.75 m thick dam wall seemed to present the greatest challenge and risk as to how to carry out this operation without losing any water from puncturing the dam. An initial idea was muted to run the pipe as a siphon over the wall and then down to the reactor. This was dismissed however, as such a pipe configuration would promote solids collection in the pipe and also require the system operator to have to prime the pipe network every morning when opening the valve. The method adopted was to pass the pipe through the wall in a two-stage method devised by the local contractor whereby the rubble stonework was removed down to the existing level of the water in the dam. The downstream level of stonework was then further lowered to the required level of the pipe, leaving half the width of the dam wall intact to preserve the water. The pipe was then laid in the downstream half and the dam built back up to above water level on this side. The upstream side was then lowered down to the level of the pipe and connected to the exposed pipe sticking through from the downstream level. The upstream, side of the dam was then reinstated.

Finally, the two sealed plastic tanks, each of 2300 litre volume, were installed in series to enable people to collect water at any time of the day or night via a tap stand from the second tank.

System operation and results

A water caretaker was appointed by the community to operate and maintain the system on a daily basis. The caretaker was trained in the operation of the system and also given a set of tools for maintenance. Every morning at 9am the downstream gate valve was opened and the flow regulated to a flow of approximately 10 litres /min. This was achieved by simply timing how long it took to fill a 20 litre jerry can at the sampling valve and adjusting the valve appropriately. The valve was then closed every night at 5 pm. In the short period of monitoring following its installation, it seemed that the system had been fully accepted by the local community, most of whom were now collecting water from the tap stand at the storage tank.

Several samples of influent raw water and effluent water from the reactor were taken over a four day period and analysed for bacteriological quality using an Oxfam / Del Agua portable water quality test kit. This showed that the maximum concentration of coliform bacteria entering the system was 10^2 CFU / 100ml – much less than the figure assumed in the design of the system. The clean water samples taken in parallel from the storage tank retuned values of 0 coliforms /100ml showing that the system was performing its disinfection process as designed. However, a more robust test of the system will occur during the rainy season where it would be expected that the quality of the water from the dam will deteriorate at the same time that the diurnal solar radiation intensities will be lower due to cloud cover.

Future development

To date the system has only been in operation for a short period of time and so it is too early to proclaim the sustainability of such a system. The long-term performance, maintenance and acceptability of the system will be monitored as well as health statistics for the local population. Incidences of water related illnesses (diarrhoea etc) are being recorded both in Ndulyani and several other local villages which have no access to such an improved water source for comparison to assess whether the improvement in the water quality translates into a long term health improvement in the community. As mentioned above a specific campaign of water quality testing will be carried out during the rainy season (late November until mid December) when the pollutant loads are potentially at their highest and solar intensities at their lowest. In parallel to this the potential of fabricating such a system in Kenya by a local company is being explored as the strategy of manufacturing such systems in Portugal and shipping them to Kenya is obviously not suitable if the technology is going to be adopted on a wider basis and does nothing to build capacity in the countries where the systems are needed.

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