Desalination and Water Treatment
www.deswater.com

doi:10.5004/dwt.2021.27335

228 (2021) 36–46
July

Development and analysis of a floating solar distillation device

Luca Caruana[a], Stephen Abela[b], Paul Refalo[a,*]

[a]*Department of Industrial and Manufacturing Engineering, Faculty of Engineering, University of Malta, Msida, MSD 2080, Malta, Tel. +356 2340 2058, emails: paul.refalo@um.edu.mt (P. Refalo), luca.caruana@um.edu.mt (L. Caruana)*
[b]*Department of Materials and Metallurgy Engineering, Faculty of Engineering, University of Malta, Msida, MSD 2080, Malta, email: stephen.abela@um.edu.mt*

Received 6 February 2021; Accepted 14 April 2021

ABSTRACT

The aim of this study was to address research gaps in the field of solar distillation through the design, construction, and testing of an inexpensive, innovative and portable, and floating solar distillation device. The developed device was designed to cater to the water requirements of third-world communities and/or communities struck by natural disasters or emergencies. The methodology followed throughout this study was that of empirical research in conjunction with the engineering product design cycle to develop a design, as well as physical prototypes which were used in testing. The knowledge gained throughout this study culminated in a final detailed product design and an associated physical prototype. The final design is transportable, simple to assemble and use. This design requires minimal input from the end-user in its operation due to the innovative implementation of a wicking material. Even though the developed solar distillation unit floats on a relatively cool body of water, it performed better than an onshore equivalent solar still by 5%. The product would cost around EUR 43 (102 EUR m^{-2}), which is significantly less than the cost of similar products currently available on the market at the time of writing.

Keywords: Solar distillation; Desalination; Floating; Low cost; Emergency

1. Introduction

More than a billion people around the world currently lack access to safe drinking water. This number is set to increase due to global population growth relative to the quantity of available freshwater sources, which in turn are being affected by various factors including global warming [1]. It is often the case that regions lacking freshwater have an abundance of brackish or saltwater and plenty of sunshine. In addition, the destruction of modern water supply infrastructure by natural disasters, or conflict, is an occurrence which unfortunately is becoming more frequent.

A review of the available literature was carried out to obtain a clear understanding of the current state of the art in solar distillation technology. The review also included an in-depth patent search to generate new and improved designs whilst addressing the design objectives defined in this study.

The major findings obtained from the literature review included various configurations of the major components which make up a floating solar distillation unit. One specific configuration consisted of an absorber with an "inverted V-shape". This shape was adopted by the team at the University of Buffalo in an attempt to maximize the absorption of solar radiation. This design employs a sheet of carbon-dipped paper which is folded into an upside-down "V" shape, as shown in Fig. 1. The edges of this paper are immersed in brine. Using this design, the team started a production rate of 2.2 L h^{-1} m^{-2} [2,3].

Another design uses a carbon-black infused wick which is used to achieve efficient heating of the saline water to be evaporated. This wick is isolated from the body of water by means of buoyancy provided by a base produced from expanded polystyrene. The company responsible for this

---

* Corresponding author.

Fig. 1. Inverted "V" shaped wick design [2,3].

product states that it purifies water at a rate four times greater than any other commercially available product. It is claimed that the raw material used in the production costs less than USD 2/m^2 [4].

The aim of this study was to design, build, and test an inexpensive, innovative, and portable floating solar distillation device under real weather conditions. Fulfilling this requirement would provide the necessary competitive advantage over existing products in the market at the time of writing. The innovative aspect of the design resulted from the floatation requirement. This characteristic allowed for opportunities in reducing the user input in the operation of the device while maximizing its performance.

The cost to purchase this product was required to be significantly less than alternative products offered on the market. The low-cost factor provided a major competitive advantage due to the relatively large expense related to the purchase of similar devices. Such an inexpensive water distiller would provide people living in developing and/or disaster-struck regions with potable water.

2. Materials and methods

2.1. Research methodology

The methodology adopted throughout this study was an empirical research methodology, specifically that of experimental research. This methodology was used by similar studies [5–9]. The engineering product design cycle was also adopted throughout this study. Subsequent designs were generated following the critical evaluation of the performance of previous designs. The engineering product design cycle is based on the Plan, Do, Check, Act (PDCA) Cycle which undergoes several iterations to generate the final detailed design. This process was used to design and construct several prototypes, which also included data acquisition systems. This was so as to test, analyze, and review the performance of the developed designs, which allowed for the generation of a successful physical concept [10].

Both the empirical research methodology and the engineering product design cycle are cyclic methodologies, which lends to their integration. Both these methodologies begin with the identification of a need. In empirical research, this "need" is then induced into a hypothesis, which is then tested in experimentation. The results obtained from testing are then evaluated and, depending on these results, the cycle is repeated [11].

The design cycle which was applied throughout this study is based on eight principal steps. These steps include [12]:

- Definition of the required product's function

With respect to this specific study, the first step of this cycle involved the definition of the function of the product. This was defined as an inexpensive, innovative and portable, floating distillation device that would enable the user to obtain fresh water from saline or brackish water.

- Problem analysis

The second step of the design cycle involved analyzing the problem which this study has set out to tackle. The problem that this product was designed to address is the freshwater requirement of developing communities or those affected by natural calamities or conflict [12].

- Definition of the required criteria

The third step involved defining the required criteria for this product. The criteria which are of major importance to the success of this product are: low cost (relative to the available capital of individuals in a disaster situation or in a developing country), the product was required to possess innovative design aspects, the product had to be designed to be easily portable and to float and function on a body of water from which the water to be evaporated is sourced. Finally, the product was required to provide the necessary freshwater from originally saline or brackish water for the user's needs [12].

- Synthesis

The synthesis of the stipulated criteria in the previous step into various designs and concepts is the fourth step of the design cycle. This represents the formation of the basic product characteristics which can be broken down into four elements. These basic elements include the form of the product; the materials used; the dimensions of the product and the surface of the components making up the product.

These elements are significant since they represent the means through which the final consumer will interact with the product [12].

- Provisional design

All the information gathered, and knowledge generated during the Synthesis phase, through the use of concept generation techniques such as morphological charts, was translated into a Provisional Design in the fifth step of the engineering product design cycle [12].

- Solution analysis

The solution analysis carried out in this study took the form of real-world testing, representing the sixth stage of the engineering design cycle.

- Comparison of results with the expected properties

The definition of the expected properties and results represents the seventh step of the design cycle.

- Evaluation of the results obtained from testing and use

The final step of the engineering design cycle is the evaluation step. This involved the comparison of the results and data obtained with the expected properties and results from the previous step. The conclusions obtained from this comparison were analyzed and used in order to develop further iterations of the product design. This was done to maximize and achieve the required properties. The engineering design cycle was applied to the three major design stages carried out in this study which included: The conceptual design stage, the embodiment design stage, and the detail design stage [12].

2.2. Design synthesis

The concept generation stage of the study consisted of an analysis of the designs and ideas which were generated in brainstorming sessions. This was done to coalesce individual ideas into a complete concept design.

A solar still is a device that consists of a top glazed cavity. The term “glazed” is used to describe the fact that the “cavity” which contains the water to be purified is covered by a surface that acts as the solar radiation transmitter and a water vapor condenser. This is typically made of glass. The water to be purified is a saline/brackish water layer, which is heated by the transmitted solar radiation. As the water to be purified is heated, it also evaporates. The water vapor is transferred from the liquid surface to a saturated air mixture through a thin diffuse interface. Heat then flows from the water vapor to the condensing or glazing surface producing an outflow of distillate. This takes place when the temperature of the condensing surface is lower than the dew point of the saturated air contained within the still [8].

A simple still is illustrated in Fig. 2. The canopy is an integral component of the device. Its purpose is to transmit solar radiation, condense water vapor, and minimize upward heat loss [13,14].

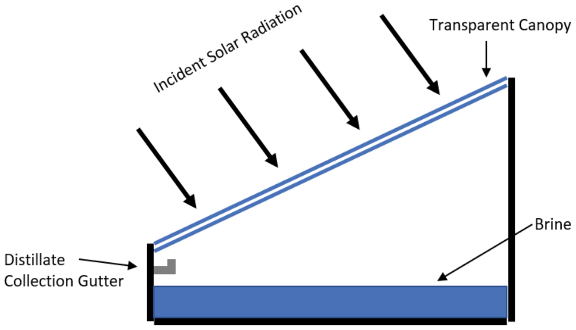

Fig. 2. Single slope passive still.

As explained previously, the distiller developed and analyzed in this study is floating solar still. the individual components and requirements of the developed prototype are explained below.

2.2.1. Floating base

The selection of the designated base shape was dependent on the following major requirements:

- Occupy a minimum of space (ease of packaging and to maximize the absorber area),
- Maximize ease of transportation,
- Maximize ease of manufacture and minimize manufacturing cost,
- Minimize area footprint when in use by endorsing a modular shape,
- Consider aesthetic design.

A circular base is aesthetically pleasing and simple in construction. It also presents an integral structure with no weak points. The issues that a circular base presents include the fact that it is more complex to manufacture when compared to a square or rectangular base manufactured from linear sections. Also, individual stills having a circular base have a larger footprint when moored together in an array fashion when compared to an array of stills having square bases for the same absorber area. Since a major requirement for this product is low cost, the manufacturing of linear section components is preferred to curved sections. A base with straight edges is also easier to transport. A square or equilateral triangle base presents the greatest benefits since the individual sides of the base are of equal dimensions and can therefore be simply divided into a number of segments for ease of transportation, resulting in a minimum total cost including manufacturing and transportation.

2.2.2. Canopy shape

The selection of the designated canopy shape was dependent on the following key requirements:

- Maximize transmission of solar radiation,
- Enhance water vapor condensation,
- Minimize shading effect,
- Possess the required structural and mechanical properties,

- Maximize ease of manufacture and minimize manufacturing cost,
- Maximize the ease of transportation of the product.

A canopy shape that can operate efficiently across a wide range of solar alignments was preferred since this maximizes the usability of the product without reducing the transmittance of incident solar irradiance. The use of a single-slope canopy was identified as the ideal canopy design so as to satisfy the above requirements and maximize the distillation performance. The angle of inclination and orientation of the sloping canopy surface is dependent on the latitude of the still's location. The optimal angle of inclination is equal to the latitude of the location when taking into consideration solely the location of the still [15].

However, the angle of inclination must be steep enough so that the condensate does not drip back off the canopy surface onto the absorber surface. An angle between 15° and 45° is recommended [15].

2.2.3. Saltwater delivery to the floating solar still

The innovative aspect of the design which was produced in this study was centered around the ability of the solar still to passively and continuously draw up sea/brackish water from the body of water on top of which the device would be made to float during operation. This continuous and passive uptake of saltwater produces a thin layer of water to be evaporated which should maximize the efficiency of the absorber system in the distillation unit [16–18].

The use of a wick is common practice in order to enhance the evaporation rate of the brine. Wicks produce a thin film of water to be evaporated and this reduces its thermal mass. Therefore, a more rapid response to solar radiation is achieved when compared to a conventional solar still which typically comprises a trough of water [18]. The most common implementation of wicks in solar distillation devices seen in the literature is the addition of wicking materials into the basin of the still. The use of floating wicks in the basin of the solar distillation unit was also noted from the literature [19–23].

2.3. Material selection

A material selection exercise for the major components was carried out. These components included the canopy, floating base, and wick material (acting also as the absorber surface) of the floating solar distillation unit. This was done since the choice of material for these components impacts on the performance of the product. The floating wick configuration adopted in this study consisted of a solid section of 100 mm thick expanded polystyrene (EPS) topped with a black 304 stainless-steel plate, which was wrapped in the chosen wick material [24].

2.3.1. Canopy material

The principal material characteristics for the canopy material used in this study were defined as:

- Maximum transmissivity for a minimum mass,
- Maximum thermal conductivity for a minimum mass,
- Maximum transmissivity for a minimum cost,
- Maximum thermal conductivity for a minimum cost,
- A suitable toughness to resist transportation and guarantee a reasonable lifespan and reliability,
- Chemical resistance to exposed conditions,
- UV stability.

Since the design generated in this study was required to be transportable, durable, and cheap, the use of glass was deemed unsuitable. Polymethylmethacrylate (PMMA) sheets were adopted for use in the generated design. This material was chosen over polycarbonate (PC) for its lower cost, whilst still possessing the required mechanical, optical, and material properties.

The optical properties of the selected canopy material (3 mm PMMA) were obtained from testing carried out at the University of Malta using a Shimadzu (Kyoto, Japan) SolidSpec-3700 spectrophotometer. This testing consisted of transmittance and absorptance testing in the ultra-violet (UV), visible (VIS), and infrared (IR) ranges. The results obtained from testing shown in Fig. 3 and Table 1 show that the transmittance of PMMA in the IR range was measured to be relatively low due to its high absorptance which in turn increases the temperature of the condensing surface. Conversely, this material presented the best compromise of all the desired characteristics during the material selection phase of this study and this conclusion only serves to indicate as a possible avenue for further improvement of the performance.

2.3.2. Base material

The use of expanded polystyrene (EPS) as the base layer has been shown in the literature to provide the required insulation to maintain the necessary temperatures within the solar still [24]. The design allows for the EPS base to serve a dual purpose: mainly as a form of thermal insulation between the body of water and the water to be evaporated, but also to provide the required buoyancy for the distillation unit to float and function on a body of water. The EPS insulating floater is topped with a black 304 stainless steel plate to act as a solar absorber.

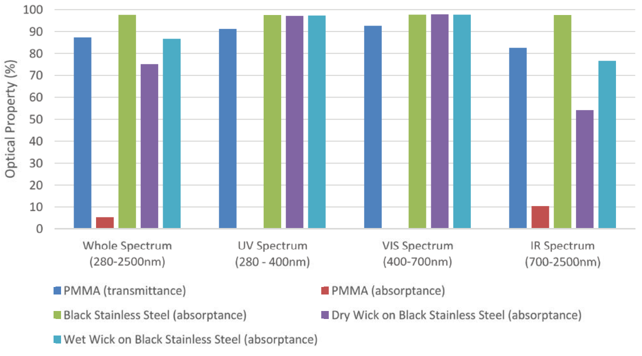

Fig. 3. Optical properties of PMMA, black stainless steel, and black polyester (wet and dry).

2.3.3. Wick material

The material selected for the wick had to be synthetic so as not to biologically degrade over time in the marine environment. Several commercially available synthetic fibers were analyzed through preliminary investigations. These fabrics consisted largely of polyester and nylon with varying thread size and weave. Wicks used in solar distillation units commonly seen in the literature include jute cloth, cotton sheets, and polystyrene sponge [14].

A capillarity height trial was carried out to aid in the selection of appropriate wick material. Four synthetic fabric materials were shortlisted as promising candidates based on their color, weave, and cost. The results of the capillarity tests are illustrated in Fig. 4. The fabric consisting of 100% polyester was selected and used in testing.

The optical properties of the absorber (black polyester wick on black stainless steel) were also measured. The wick was tested both wet and dry. The absorptance of black stainless steel was found to be consistently higher than 97% in all ranges. However, when covered with the black dry polyester wick, the absorptance reduces drastically in the IR range from 97.5% down to 54.2%. When covered with a wet wick, the IR absorptance increases to around 77% which is still lower when compared to the uncovered stainless steel plate. The thin water layer present in the wick material reflects approximately 22% of the incident IR radiation. When considering the whole spectrum of solar radiation, wetting the wick increases its absorptance from 75% to 87%. When the IR transmittance of the PMMA canopy (82.6%) and the IR absorptance of the wet wick (76.6%) are considered, one concludes that only 63% of the IR energy makes it to the evaporation surface.

2.4. Final design

The design iterations and lessons learned during preliminary testing were assimilated into a final detailed design which comprises the use of an EPS base that could be disassembled into a number of different sections for improved packaging and transportation. The absorber/evaporator measures 0.65 by 0.65 m. The whole floating distillation unit has a footprint of 0.9 by 0.9 m. The wick height was maximized to the height of the surrounding floating base in order to minimize the shadowing effect of adjacent components. The complete 3D model is illustrated in Fig. 5. This consists of a trapezoidal canopy which is seated on eight individual EPS base sections secured together to form the complete floating base. The main floating unit is connected to a fresh waste collection system via a tether and a distillate delivery hose which is submerged under the body of water. The position of the freshwater collection system under the surface of the body of water is indicated by a separate float.

The product developed in this study was designed to be tightly packaged whilst maximizing the available volume resulting in a transportable design, which is illustrated in Fig. 6. The design is simple to assemble and use and requires minimal input from the user in its operation. This will aid the successful adoption of this product in its intended point

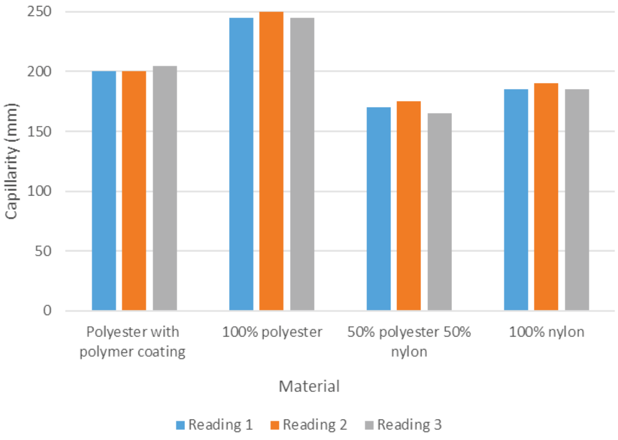

Fig. 4. Results of wick material capillarity.

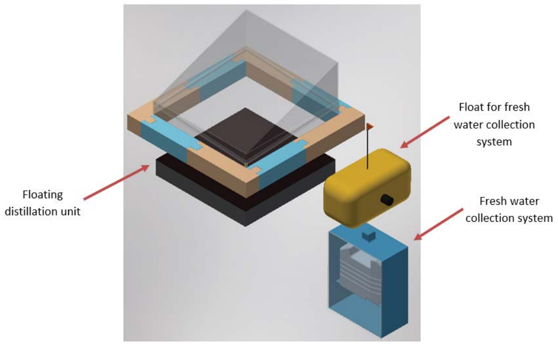

Fig. 5. 3D model of the floating solar distillation device.

Table 1
Optical properties of PMMA, black stainless steel, and black polyester (wet and dry)

Spectrum	Transmittance (%)	Absorptance (%)			
	PMMA Canopy	PMMA Canopy	Black stainless steel	Dry wick on black stainless steel	Wet wick on black stainless steel
Whole spectrum (280–2,500 nm)	87.3	5.4	97.6	75.1	86.7
UV (280–400 nm)	91.2	0.4	97.5	97.1	97.3
VIS (400–700 nm)	92.6	0.0	97.7	97.8	97.7
IR (700–2,500 nm)	82.6	10.4	97.5	54.2	76.6

of use. The gross cost of this product is estimated to be around EUR 43 (102 EUR m^{-2}) taking into consideration all the attributed manufacturing costs such as raw materials, investment in machinery, and other assets and wages. This is significantly less than the cost of similar products currently available on the market such as the inflatable emergency solar stills which are commercially available and cost between USD 240 and 330 [25]. This low cost is appealing since it encourages widespread adoption in emergency situations and in developing countries.

Fig. 7 is a schematic illustrating the operation of the floating solar distiller. The red arrows indicate how to brine is drawn up from the body of water into the wick material. This wicking material, being the absorber, is incident with solar irradiance which causes the brine to evaporate and rise towards the canopy where it condenses, as is illustrated by the brown arrows. This condensate is then collected in a trough and is fed out of the floating distillation unit by gravity as illustrated by the black arrows. The condensate then flows to the submerged freshwater collection unit via a connecting pipe where it is then stored.

3. Testing phase

3.1. Experimental Setup

Testing of the developed floating prototype was carried out concurrently using an equivalent onshore solar still consisting of the same evaporating and condensing areas and materials. The onshore solar still was used as a benchmark to obtain a clear measure of the developed design's performance over that of a known baseline within this sector. The basin of the onshore solar still was filled with 20 mm of water. A schematic diagram of the equivalent simple still is shown in Fig. 8.

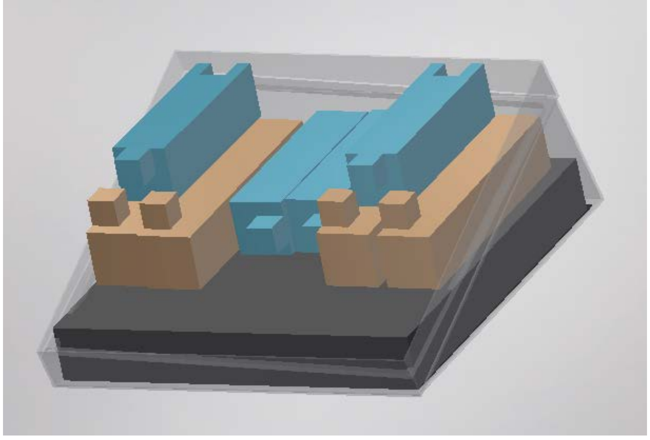

Fig. 6. Floating solar still designed for packaging and transportation.

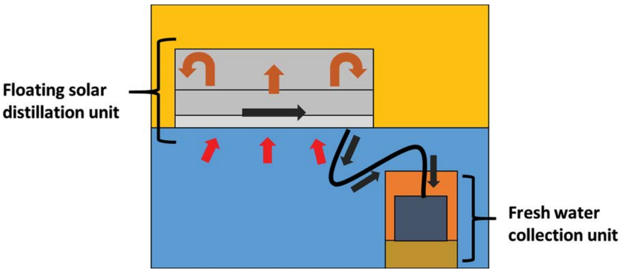

Fig. 7. Schematic representation of the floating solar distillation device.

The testing of the floating solar still was carried out in an open-top 1,500 L water tank present on the roof of a building fully exposed to natural elements. Both prototypes were tested under the same climatic conditions to ensure that both the developed prototype and the equivalent simple solar still were exposed to the same weather conditions establishing a fair basis for comparison [26]. A weather station was used to measure the meteorological conditions of the microclimatic parameters during testing.

3.2. Collection of test data

Various methods have been described in the literature to quantify the volume of distillate obtained from a solar still [26]. A data collection system was integrated within the prototype design to collect data on the operating mechanism. The evaporation–condensation process which takes place within a solar still is driven by the temperature difference between the absorber and condensing surfaces. For this reason, the measurement of this temperature difference illustrates the thermodynamic mechanism taking place within the still. This data collection system made use of Omega Type-T Class 1 thermocouple (diameter 0.5 mm, resolution 0.1°C accuracy ±0.5°C) to measure the temperature of the water vapor and surfaces at different positions in the solar still. All surface temperature-measuring thermocouples were adhered to the surface using a water-resistant rapid-setting epoxy adhesive

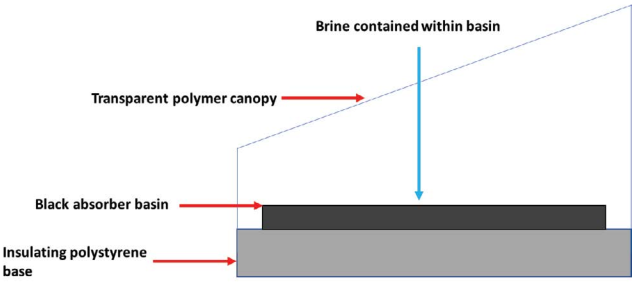

Fig. 8. Onshore simple solar still.

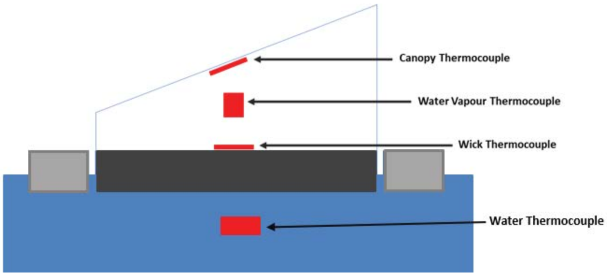

Fig. 9. Location of thermocouples on the floating solar distiller.

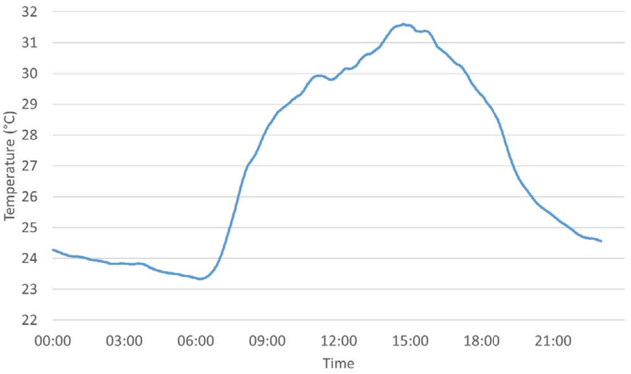

Fig. 10. Average daily variation in ambient temperature over the entire testing period.

(Araldite–Rapid). The location of the thermocouples on the developed design is illustrated in Fig. 9. The canopy and water vapor thermocouples were shielded from direct solar radiation.

An electronic scale (resolution: 0.01 g, accuracy: ±0.02 g, and combined uncertainty: ±0.02 g) was used to measure the distillate regularly throughout the day. The dimensions of the manufactured absorbers/evaporators were measured using a measuring tape (resolution: 1 mm, accuracy: ±0.5 mm, measurement uncertainty: ±5 mm, and combined uncertainty: ±5.1 mm). An uncertainty analysis was conducted on the specific performance of the solar stills (L m^{-2} d^{-1}). The analysis resulted that the overall uncertainty amounts to around ±0.022 L m^{-2} d^{-1}.

4. Results and discussion

The average variation in ambient temperature during a typical day of testing during the testing period is illustrated in Fig. 10. An average maximum temperature of just below 32°C was recorded at approximately 14:00. A minimum average temperature of just above 23°C was recorded at approximately 06:00. A Kipp and Zonen CMP6 1st Class Pyranometer was used to measure the solar irradiance. The average daily variation in solar irradiance for a typical day of testing is depicted in Fig. 11. A maximum solar irradiance of approximately 950 W/m^2 was recorded at 13:00. This is typical for the period between the months of June and September in Malta as was recorded by Refalo during a similar time of year [28]. The average daily variation in wind speed for the period of testing is shown in Fig. 12. The average maximum wind speed recorded during this period was approximately 1.80 m/s. This is equivalent to a force of 2 on the Beaufort wind scale and represents a light breeze which is typical during the summer months of Malta. The cooling effect of elevated wind speeds on the solar distillation units was considered to be minimal.

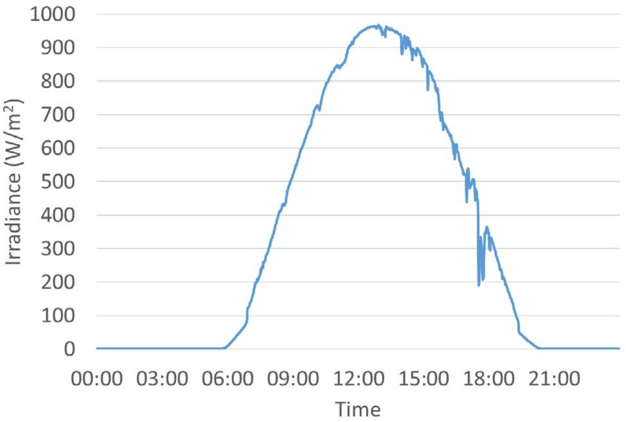

Fig. 11. Average daily variation in solar irradiance over the entire testing period.

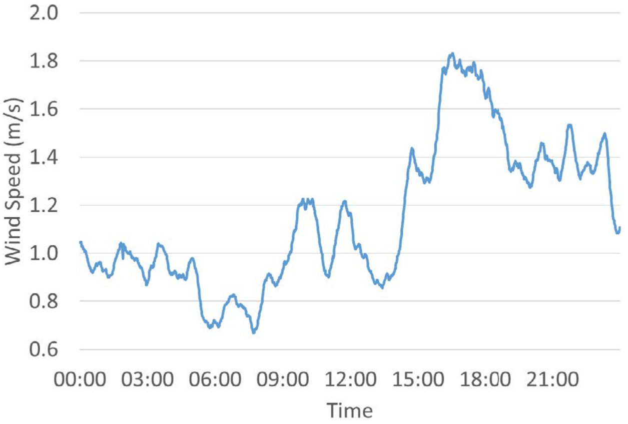

Fig. 12. Average daily variation in wind speed over the entire testing period.

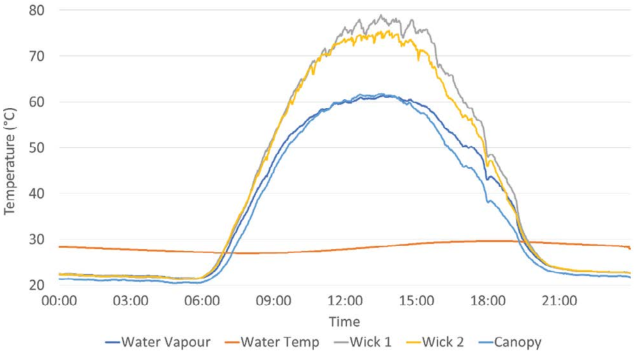

Fig. 13. Average daily floating still temperatures observed over the entire period of testing.

The average daily solar still temperatures are shown in Fig. 13. A significant temperature difference between the wick (absorber) surfaces and the canopy (condensing) surface is depicted in this graph. A maximum wick temperature of approximately 80°C was recorded at 13:00. The canopy and water vapor temperature were very similar with a minimal temperature difference observed between the two components in the floating distillation unit. The maximum temperature of the water vapor and the canopy material hovered just above 60°C. The water in the 1,500 L tank, which simulated the body of water on top of which the still was made to float, had a temperature that was consistently at around 30°C.

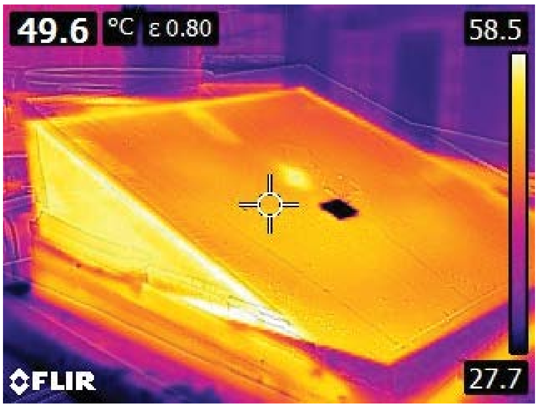

Fig. 14. Thermal image of the floating solar still during testing.

A thermal image of the floating solar still during testing is illustrated in Fig. 14. This image was taken at 11:00 (2 h before solar noon) during the summer months of 2019 in Malta. The areas which are white in color are at a temperature of approximately 58°C, this corresponds to the maximum temperature of the canopy recorded at this time.

The average daily variation in temperature difference between the wick (absorber), water vapor, and canopy (condenser) during testing of the floating still is illustrated in Fig. 15. The daily variation in temperature difference "wick surface – water vapor" and "wick surface – canopy surface" follow a similar pattern with a maximum temperature difference of approximately 15°C. These two profiles of temperature difference are similar since a small temperature difference was recorded between the water vapor and the canopy as can be seen in Fig. 15. Between 12:00 and 13:00, the canopy had a recorded temperature which was slightly greater than that of the water vapor. This is due to the relatively high solar absorptance of the canopy material when compared to other typical canopy materials, such as low iron glass [28]. This caused the canopy material to increase in temperature to a point that was approximately equal to that recorded for the water vapor at the same time. This resulted in a relatively low still efficiency of 12% when compared to a typical simple still which operates with a thermal efficiency of between 35% and 40% as described in the literature [29,30]. The temperature differences depicted in Fig. 15 indicate a possibility for increased performance of the floating still by reducing the condenser (canopy) temperature in order to increase the temperature difference between the water vapor and the condenser cover. Reducing the temperature of the canopy material will increase the temperature difference between the condenser and the absorber surface further, driving the evaporation–condensation process exponentially. The temperature of the canopy material can be reduced by selecting a material with a greater transmissivity of solar radiation in the infrared range. A material with an improved transmissivity used in literature consisted of low iron glass with a measured transmittance of 90%. An average temperature difference of 8°C was recorded between the water vapor and condensing surface (low iron glass) of a simple still during testing carried out by Refalo [28].

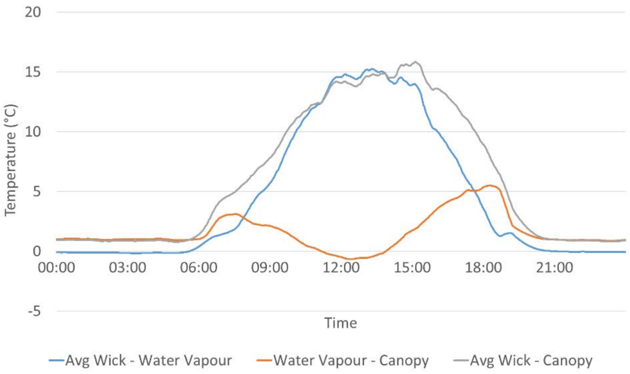

Fig. 15. Temperature differences on a typical day of testing between the absorber (wick), water vapor, and condenser (canopy) surfaces of the floating solar still.

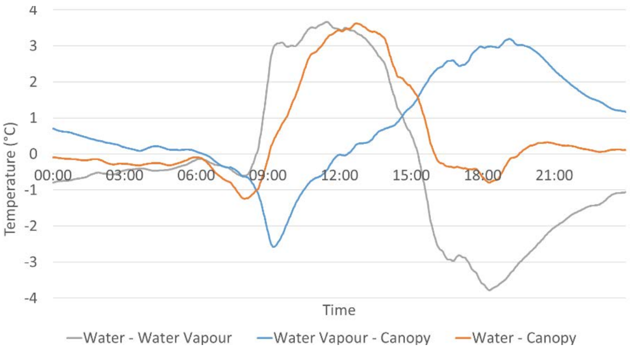

Fig. 16. Temperature differences on a typical day of testing between the water to be evaporated, water vapor, and condenser surfaces during testing of the onshore solar still.

The average variation in temperature difference between the water to be evaporated, water vapor, and canopy (condenser) during testing of the benchmark onshore solar still is illustrated Fig. 16. The maximum temperature differences are much lower than those recorded for the floating solar still, with maximum temperature differences recorded below 4°C.

Inadequate wetting of the wick material during testing of the floating still was noted during testing. Additionally, the high wick temperatures (Fig. 13) indicate that the water flow through the wick capillaries was not able to replenish the water in the wick material at a rate that matched that of the evaporation rate. Consequently, the material became progressively drier over the period of a day of testing. As concluded from the spectrophotometer tests, drying the material not only reduces the amount of water for evaporation but also decreases the solar absorptance of the material. Hence, improving the wicking mechanism to increase the volume of water present in the wick material will improve the performance of the floating still.

The average daily variation in the production rate for both the floating still and the equivalent simple still is depicted in Fig. 17. Both the simple still and the floating still behave very similarly with a slightly higher production rate achieved by the floating still at 14:00, this was above 100 mL/m^2 h. The maximum productivity achieved by the onshore solar still was below 100 mL/m^2 h. Given that the floating still was operating at a lower solar absorptivity and since inadequate wick wetting was also observed, this slightly better performance is a promising result from the design developed in this study.

The required daily productivity set at the start of the study was 3–4 L m^{-2} d^{-1}. This requirement was set as it reflects the typical productivities achieved in the studies investigated in literature [29,30]. The average productivity achieved during testing of the floating solar still was 1.45 L m^{-2} d^{-1} (±0.02 L m^{-2} d^{-1}) while the onshore solar still produced 1.38 L m^{-2} d^{-1} (±0.02 L m^{-2} d^{-1}) of potable water. The productivity of the floating solar distillation unit was slightly higher than that of the onshore solar still by 5%. The floating solar still outperformed the equivalent onshore simple solar still due to the perfectly thin layer of water to be evaporated present in the wick when compared to the larger volume of water present in the basin in the onshore still. The water present in the wick of the floating still consists of a much smaller thermal mass than that of the volume of water present in the basin of the onshore simple still. This allows the water in the wick to achieve the required evaporation temperature quicker than that of the onshore simple still thus producing more water vapor and the resulting condensate over the period of a day. The lower productivity achieved, when compared to the daily productivity of 3–4 L m^{-2} d^{-1} set at the start of the study, was due to the relatively high canopy (condenser) temperature which led to a minimal temperature difference between the water vapor and the canopy surface. This is mainly due to the relatively high absorptance and low transmittance of PMMA in the infrared ranges. These optical properties increased the temperatures of both condensers in the floating and onshore solar stills decreasing and blocking both the evaporation and condensation processes.

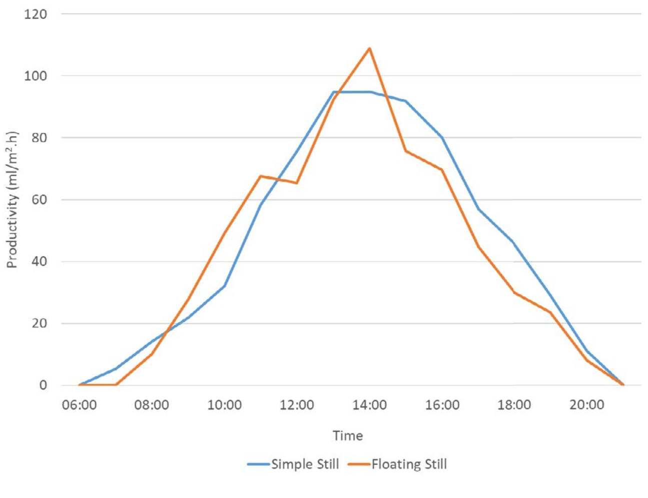

Fig. 17. Average productivity over the period of a typical day of testing for both the floating solar still and the onshore solar still.

A second reason for the lower productivity was the observed inadequate wetting of the wicking floating evaporator. This caused the wick of the floating solar still to have an insufficient volume of water present in the material during peak evaporation temperatures. The drying of the evaporator obviously resulted in a lower evaporation process but also increased the temperature of the water vapor and the condenser. In return, the higher temperature of the latter further results in lower evaporation and condensation processes. Nonetheless, it was shown that the floating still, with its limitations, performed as well as a typical solar still with the extra benefit of passive refilling of the evaporator.

5. Conclusions

In this study, an inexpensive and viable design was developed and tested to provide fresh drinking water from water that was originally unfit for human consumption. The device was designed to float on the body of water from which the water to be purified was passively drawn.

The contribution to knowledge made through this study is centered around the innovative implementation of a floating wick absorber. This innovative aspect was employed in a product design at a cost that is significantly less than the cost of similar products. This innovative aspect was tested under real-world conditions whilst confirming its successful operation by comparing its performance to an equivalent simple still. Such a direct comparison for a design incorporating a floating evaporator was not previously available in the literature considered.

It was shown that even though the productivity (at circa 1.45 L m^{-2} d^{-1}) is relatively lower than that of typical solar stills described in the literature, the tested floating still was as efficient (or slightly better) as its onshore counterpart which was used as the benchmark. The materials selected for the manufacturing of the floating and benchmark stills were chosen keeping low cost and portability into consideration. This had a direct impact on the productivity of the developed and tested stills.

Moreover, this study showed that in order to improve the performance of the floating still, a canopy with a higher solar transmittance and a better wicking configuration should be used. These will exploit the full benefits of having a floating absorber supplied passively and consistently with a thin film of water.

The gross cost of the floating still is around EUR 43 (102 EUR m^{-2}) which is significantly lower than the cost of similar products currently available on the market such as the inflatable emergency solar stills which are commercially available and cost between USD 240 and 330 [25].

There are various ways in which such a floating solar distiller can be improved. An optimization study based on the various design parameters of the floating unit could be performed. Such parameters include the optical properties of the canopy, capillarity of the wicking material, dimensions of the floating evaporator/wicking area, and others. This study has shown how the absorptance and the transmittance of the canopy have a direct impact on the performance of the solar distillers. Hence, it is envisaged that testing with other durable and inexpensive materials which have better optical properties will result in a better yield. The wick height, or capillarity height, is dependent on the height of the base used (which serves as a floater and insulator). The optimal height can be identified by investigating the loss of thermal energy through the height of the insulation between the surface of the body of water and the absorber surface. Reducing the insulation height will also reduce the height through which the water to be evaporated needs to travel and hence ensures consistent wettability of the evaporator. The floating distiller developed in this study was tested in a water tank. To further understand the performance of such a device, it would be sensible to test the floating unit in a real body of water such as the sea or a lake. A long-term study carried out *in-situ* would not only yield results on the performance of the unit but would also provide feedback on the eventual transportation, packaging, and maintenance of the product by the end-user.

Through the generation of physical concepts and real-world testing results, a viable solution for the provision of freshwater to water-stressed regions and/or regions impacted by conflict or natural disasters has been generated and can now be presented to potential manufacturers and investors such as water conservation, sanitation, health promotion, and disaster relief organizations.

Acknowledgments

This study was carried out as part of the project Floating SolDi funded through the Maritime Seed Award 2017 (MarSA) by TakeOff (University of Malta) and Malta Marittima (Government of Malta). The authors would also like to thank Prof. Luciano Mule Stagno and Dr. Ing. Daniel Micallef from Innova, Malta for their contribution to the project.

References

[1] A. Delyannis, E. Delyannis, Recent solar distillation developments, Desalination, 45 (1983) 361–369.

[2] H. Song, Y. Liu, M.H. Singer, C. Li, A. R. Cheney, D. Ji, L. Zhou, N. Zhang, X. Zeng, Z. Bei, Z. Yu, S. Jiang, Q. Gan, Cold vapor generation beyond the input solar energy limit, Adv. Sci., 5 (2018) 1–8.

[3] E. Matcher, Could This Low-Cost Device Provide Clean Drinking Water To Those in Need?, Smithsonian Magazine, 2018. Available at: https://www.smithsonianmag.com/innovation/could-this-low-cost-device-provide-clean-drinking-water-to-those-in-need-180969100 (accessed April 03, 2019).

[4] F. Robert, Sunlight-Powered Purifier Could Clean Water for the Impoverished, Science, 2017. Available at: http://www.sciencemag.org/news/2017/02/sunlight-powered-purifier-could-clean-water-impoverished (accessed June 09, 2019).

[5] UNISDR – United Nations Office for Disaster Risk Reduction, Annual Report 2011, United Nations, Geneva, 2011.

[6] K. Jijakli, H. Arafat, S. Kennedy, P. Mande, V.V. Theeyattuparampli, How green solar desalination really is? Environmental assessment using life-cycle analysis (LCA) approach, Desalination, 287 (2012) 123–131.

[7] P.T. Tsilingiris, Combined heat and mass transfer analyses in solar distillation systems - The restrictive conditions and a validity range investigation, Solar Energy, 86 (2012) 3288–3300.

[8] B.I. Ismail, Design and performance of a transportable hemispherical solar still, Energy, 34 (2009) 145–150.

[9] C. Reichardt, Experimental and Quasi-Experimental Designs for Generalized Casual Inference, Houghton Mifflin, Boston, MA, 2002.

[10] A. Bhar, Empirical Research: Definition, Methods, Types and Examples, QuestionPro. Available at: https://www.questionpro.com/blog/empirical-research/ (accessed June 13, 2018).

[11] G.N. Tiwari, Solar Energy Fundamentals, Design, Modelling and Applications, Harosa Publishing House Private Limited, New Delhi, 2002.

[12] K. Otto, K. Wood, Product Design, Techniques in Reverse Engineering and New Product Development, Prentice Hall, New Jersey, 2001.

[13] P. Kalita, A. Dewan, S. Borah, A review on recent developments in solar distillation units, Sadhana, 41 (2016) 203–223.

[14] K. Kalidasa Murugavel, K. Chockalingam, K. Srithar, Progresses in improving the effectiveness of the single basin passive solar still, Desalination, 220 (2008) 677–686.

[15] A.N. Minasian, A.A. Al-Karaghouli, A floating-wick type solar still, Renewable Energy, 6 (1995) 77–79.

[16] C. Li, G.P. Peterson, Y. Wang, Evaporation/boiling on thin capillary wick (I): thickness effects, J. Heat Transfer, 128 (2006) 1312–1319.

[17] A.K. Tiwari, G.N. Tiwari, Effect of the condensing cover's slope on internal heat and mass transfer and mass transfer in distillation: an indoor simulation, Desalination, 180 (2005) 73–88.

[18] J.G. Modi, K.V. Modi, A review on solar still augmented with wick materials, Int. J. Adv. Res. Innovative Ideas Educ., 3 (2017) 3737–4720.

[19] Y. Ho-Ming, C. Lie-Cheng, The effects of climatic, design and operational parameters on the performance of wick type solar distillers, Energy Convers. Manage., 26 (1986) 175–180.

[20] S.H. Sengar, A.G. Mohod, Y.P. Khandetod, S.P. Modak, D. K. Gupta, Design and development of wick type solar distillation systems, J. Soil Sci. Environ. Manage., 2 (2011) 125–133.

[21] J.T. Mahdi, B.E. Smith, A.O. Sharif, An experimental wick-type solar still system: design and construction, Desalination, 267 (2011) 233–328.

[22] V. Velmurugan, M. Gopalakrishnan, R. Raghu, K. Srithar, Single basin solar still with fin for enhancing productivity, Energy Convers. Manage., 49 (2008) 2602–2608.

[23] Continental Steel and Tube Company, Stainless Steel Grades, 2019. Available at: https://continentalsteel.com/stainless-steel/grades/ (accessed February 04, 2019).

[24] L. Zhejun, S. Haomin, J. Dengxin, L. Chenyu, C. Alec, L. Youhai, Z. Nan, Z. Xie, C. Borui, G. Jun, L. Yuedheng, L. Xiang, A. Diana, J. Suhua, Y. Zogfu, G. Qiaoqiang, Extremely cost-effective and efficient solar vapour generation under nonconcentrated illumination using thermally isolated black paper, Global Challenges, 1 (2017) 1–10, doi: 10.1002/gch2.201600003.

[25] Landfall Navigation, Landfall Navigation Aquamate Solar Still. Available at: http://www.landfallnavigation.com/memss.html (accessed February 23, 2018).

[26] P. Refalo, R. Ghirlando, S. Abela, The use of a solar chimney and condensers to enhance the productivity of a solar still, Desal. Water Treat., 57 (2016) 23024–23037.

[27] P. Refalo, R. Ghirlando, S. Abela, Temperature Measurement in Solar Thermal Applications, Proceeding of International Solar World Congress, Kassel, Germany, 2011.
[28] P. Refalo, Innovative Approaches to Solar Distillation, Faculty of Engineering, University of Malta, 2015.
[29] J. Lindblom, Solar Thermal Technologies for Seawater Desalination: State of the Art, Lyngby, Ed., Solar Energy: State of the Art, Danmarkks Tekniske Universitet, Denmark, 2003, pp. 93–108.
[30] M.A. Samee, U.K. Mirzza, T. Majeed, N. Ahmad, Design and performance of a single basin solar still, Renewable Sustainable Energy Rev., 11 (2007) 543–549.