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PERFORMANCE STUDY ON TUBULAR SOLAR STILL

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ABSTRACT
This study aims to provide a low cost solar still using locally available materials to meet small-scale fresh water demand in the coastal, arid and remote regions. In this study a tubular solar still (TSS) was designed, constructed and field experiment have been carried out at Khulan University of Engineering & Technology since 2008. It is comprised of tubular frame (1m long and 20cm in diameter, made of 2.75 mm GI wire) covered with a transparent normal polythene paper and a black rectangular trough (1.0 m long, 16 cm width, 5 cm deep, made of carton paper) for storing saline water. The average daily production rate for the TSS was found as 3.03 lit/m^2-day, with highest and lowest values were 3.81 and 1.79, respectively. Highest productions were observed in April-June and lowest in December-January. The initial cost for the preparation of each TSS was only Tk. 80 and the production cost of the distilled water was Tk. 0.39 Tk./lit. It is concluded that due to low initial cost and also the easier construction, operation and maintenance of TSS than Basin type Still, one can easily use a TSS for drinking and other purposes in remote, coastal and arid areas or in an emergency to meet small scale fresh water demand.

Keywords: *Ambient air temperature, Basin type Solar Still, Desalination, Salinity, Solar energy, Tubular Solar Still (TSS).*

1. INTRODUCTION

Water is one of the most abundant resources on earth, covering three-fourths of the planet's surface. In the world, demand of portable fresh water is increasing day by day because of population explosion all over the world, greater industrial development, expansion of agricultural activities and climate change. Now it is recognized that freshwater is a scare resources and more country is converted into water-stressed country due to the scarcity of freshwater resources. There is an almost unfathomable amount of water on earth: about 1.4 billion km^3 (330 million cubic miles) (Barlow and Clark, 2002). About 97% of the earth's water is salt water in the oceans and a tiny 3% (about 36 million km^3) is fresh water contained in the poles in the form of ice, ground water, lakes and rivers, which supply most of human and animal needs (Ahmed and Rahman, 2000). Nearly, 70% from this tiny 3% of the world's fresh water is frozen in glaciers, permanent snow cover, ice and permafrost. Thirty per cent of all fresh water is in underground, most of it is in deep, hard-to-reach aquifers. Lakes and rivers together contain just a little more than 0.25% of all fresh water; lakes contain most of it (Kalogirou, 2005). The data relevant to water requirements shows that around 25% of the total world populations do not have an adequate fresh water supply, both for quality and quantity (Agha et al., 2005). Water shortages affect 88 developing countries that are home to half of the world's population. In these places, 80-90% of all diseases and 30% of all deaths result from poor water quality (Leitner, 1998). Furthermore, over the next 25 years, the number of people affected by severe water shortages is expected to increase fourfold (Engelman et al., 2000). Some of this increase is related to population growth, some is related to the demands of industrialization. Currently, water consumption doubles every 20 years, about twice the rate of population growth (Barlow and Clark, 2002). The ground water source is being polluted by organisms, organic and inorganic compounds due to the ultimate disposal of man-made harmful pollutant into the underground reservoir (Malik et.al, 1982). In the coastal region of Bangladesh, salinity in water poses a serious problem for the communities in the affected area. The increase in salinity in Khulna region started after the commencement in 1975 of the Farrakka Barrage operation in India, which significantly reduced the flow in the Ganges, located at upstream of the Gorai River, a

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major source of freshwater to the rivers surrounding Khulna. At present, the principle cause of salinity intrusion in Khulna region is the drop of hydraulic head during the dry period (November to May) into both surface and groundwater of the area (Hassan et al., 1998). Although this communities are virtually surrounded by water but practically they suffer due to lack of drinkable water. There are deep aquifers containing water of acceptable salinity for human consumption; but the deep aquifers containing sweet water are not found at all possible locations. Thus the removal of salinity is immense for the population of those regions to obtain sufficient amount of potable water by mixing saline water with distilled water. One of the alternative sources of potable water for this area appears to be the development of the appropriate desalination technology.

Most desalination techniques consume a large amount of energy. Moreover, many remote towns and communities rely on costly and often limited supplies of diesel fuel for their energy needs. These and other forms of fossil fuels are sometimes heavily subsidized by government to meet community service obligations (Water Corporation, 2000). Therefore finding methods of using renewable energy to power the desalination process is desirable. Solar distillation is the simplest desalination technique, compared with other types, e.g., multiple-effect distillation, multi-stage flash, reverse osmosis, electro-dialysis and biological treatment due to no need of fossil fuel or electricity. The main disadvantage of solar distillation is its low productivity of distillate but although it may also be one of the viable options for providing drinking water for a single house or a small community in arid or remote regions. A basin-type solar still is the most popular method of solar distillation, but main drawbacks of the basin type are not easy of construction and the difficulty in rapid and easy removal of basin accumulated salt. Therefore, we designed a new type of low cost of solar distillation unit, Tubular Solar Still (TSS), to overcome such difficulties in the maintenance and management. It is comprised of tubular frame covered with a transparent polythene paper and a trough for storing saline water. In this study, a low cost TSS was designed, constructed and field experiments have been carried out at Khulna University of Engineering and Technology (KUET) since January 2008.

2. METHODOLOGY

A low cost Tubular Solar Still (TSS) is designed and constructed using locally available materials. It is consisted of Tubular frame covered with a transparent normal polythene paper and a black rectangular trough for storing saline water. Field experiments are conducted using the constructed TSS. Daily distilled water production and hourly production of some typical days are recorded. Collected data was analyzed and correlations are proposed for daily output. Finally, the water production cost is estimated and cnclusions are drawn.

3. PRODUCTION PRINCIPLE OF TSS

Production principle of TSS is illustrated in Figure 1. The solar radiation, after transmission through a transparent polythene cover, is mainly absorbed by saline water in the trough. The tubular cover and trough absorb the remaining small amount of the solar energy. Thus the water in the trough is heated and then begins to evaporate. Many types of heat transfer occur inside the tubular cover and outside, e.g., evaporative heat transfer from the saline water to the tubular cover, condensative heat transfer from the saline water and the tubular cover, the trough and the water, the trough and the tubular cover and the cover and the atmosphere, radio-active heat

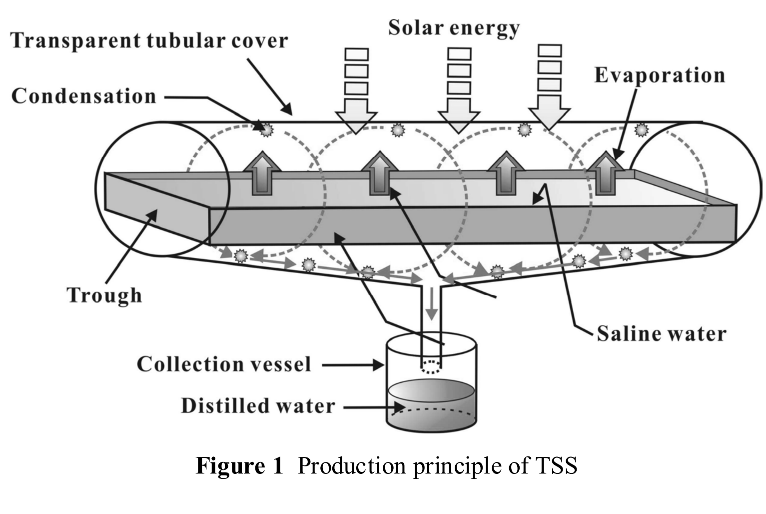


Figure 1 Production principle of TSS

transfer between the water surface and the tubular cover and the tubular cover and the atmosphere. The evaporative water is transferred to the tubular cover and then finally condensed on the tubular cover inner surface, releasing its latent heat of vaporization. The condensed water trickles down the bottom of the tubular cover inner surface due to gravity and is stored in a collection bottle through a pipe provided at the middle.

4. DESIGN, CONSTRUCTION AND FIELD EXPERIMENT

4.1 Design and Construction of Tubular Solar Still

TSS is consisted of tubular frame covered with a transparent normal polythene paper and a black rectangular trough for storing saline water. The Tubular frame is 1.00 m long, 20 cm in diameter and is comprised of 2.75 mm thick helical G.I wire. The pitch of the spiral ring is about 5 cm. The trough is 1.0 m long, 16 cm width, 5 cm deep and is made of carton paper (painted black inside) covered with black polythene. The schematic diagram of the TSS is shown in Figure 2.

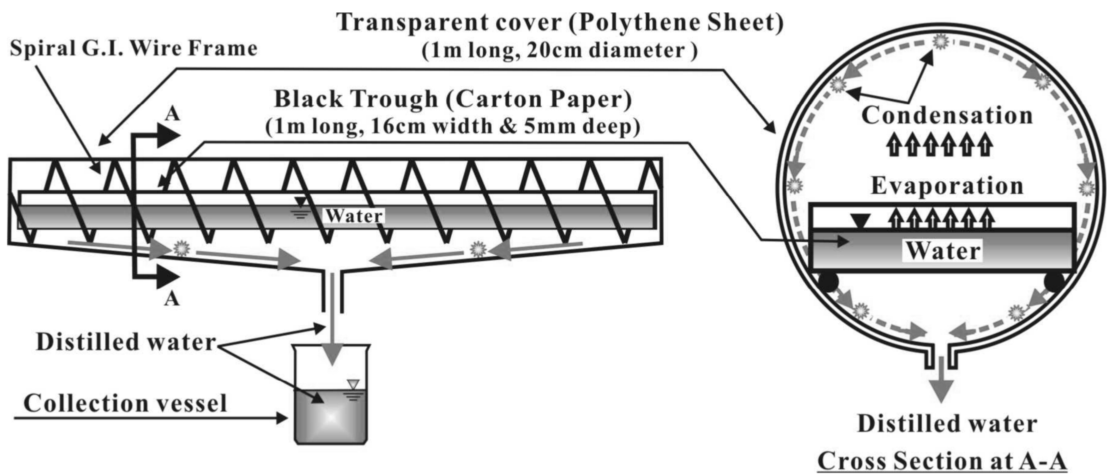
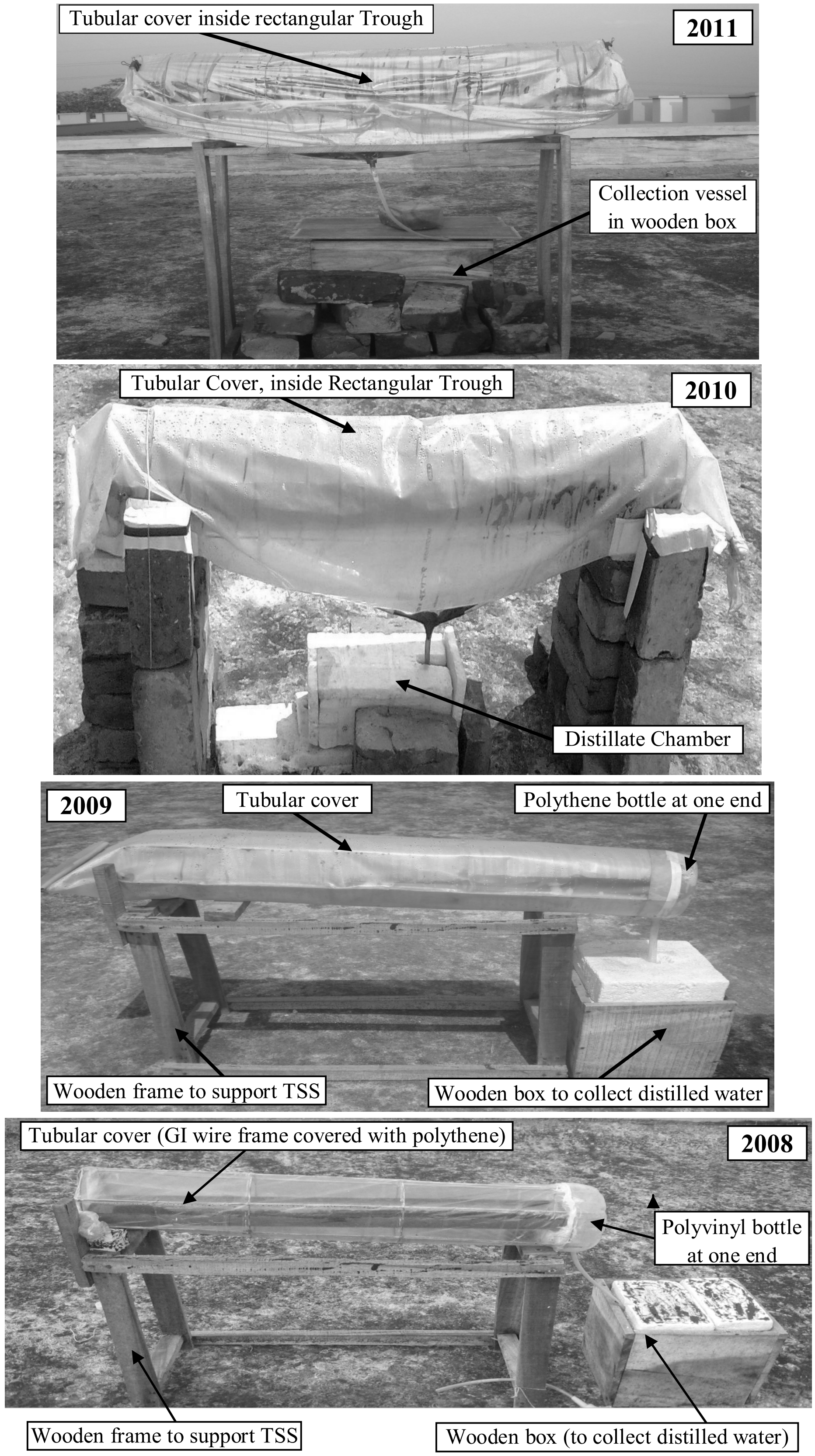


Figure 2 Schematic diagram of the TSS

4.2 Field Experiment

The field experiments have been carried out on the roof top of the Civil Engineering building of Khulna University of Engineering and Technology (KUET) since January 2008. Figure 3 shows the photograph of the field experiment. A wooden frame was used to support the TSS so that free circulation of air occurs beneath the still. The vessel for distilled water collection was put in a wooden box covered (inside) with styrofoam (heat insulator) in order to collect the amount of distilled water from the TSS accurately. One end of the TSS was kept fixed and other end could open to clean the trough or to remove the accumulated brine and to feed the saline water in the trough. The daily output from the still is collected approximately two hours after sunset. The hourly output was also measured for some typical days. The hourly outputs were also measured in some typical days to observe the hourly variation of the productivity of the still. Solar radiation flux and ambient air temperature were also measured at one minute interval using a data logger. A pyranometer and thermocouple were used to measure the solar radiation flux and temperature, respectively.

In the year 2010, the TSS was 1.20m long, 22cm in diameter and the trough was 1.18m long, 16cm width and and 5 cm deep and made of carton paper covered with black polythene sheet. Whereas, in the year 2008 and 2009, it was composed of a tubular copper frame covered with a transparent polythene paper and a black semicircular trough made of black polyvinyl chloride for storing saline water. In the year 2008, it was 80cm long, 15cm in diameter and the trough was 75cm long, 11cm in outside diameter and 1mm thickness. Wheres, it was 95 cm long, 15 cm in diameter and made of 5 mm diameter hollow copper pipe and the trough was 90cm long, 15cm in outside diameter and 1mm thickness. Also, the TSS was kept inclined downward at one end and a transparent bottle of 5cm long at that end was set to collect the distilled water output.



5. ANALYSIS AND RESULTS

Figure 3 Photograph of field experiment on TSS at KUET, Khulna

Hourly and dailty distilled water output from the TSS are used to calculate the daily and hourly production rate per unit surface area of the saline water in the trough. Figure 4 shows the observed diurnal variations of hourly production per unit saline water surface area, solar radiation flux and ambient air temperature for the TSS at KUET, Khulna for March 18 of 2010. It is observed from the figure that the solar radiation flux rose rapidly after sunrise (approximately 6:30) and peaked approximately 12:00 after declining gradually. The air temperature also rose gradually in the morning (approximately 7:00) till 13:00, and declined gradually in the afternoon. Whereas the production was recorded from 9:00 in the morning (clearly indicating that there is a distinct time lag between evaporation and production or condensation), increased gradually up to 13:00, and then declined in the afternoon. It was also seen that the slope of the hourly production rate in the morning is steeper than that of the afternoon. The total distillate output for the day is found as 3.76 lit/m^2 (602 ml).

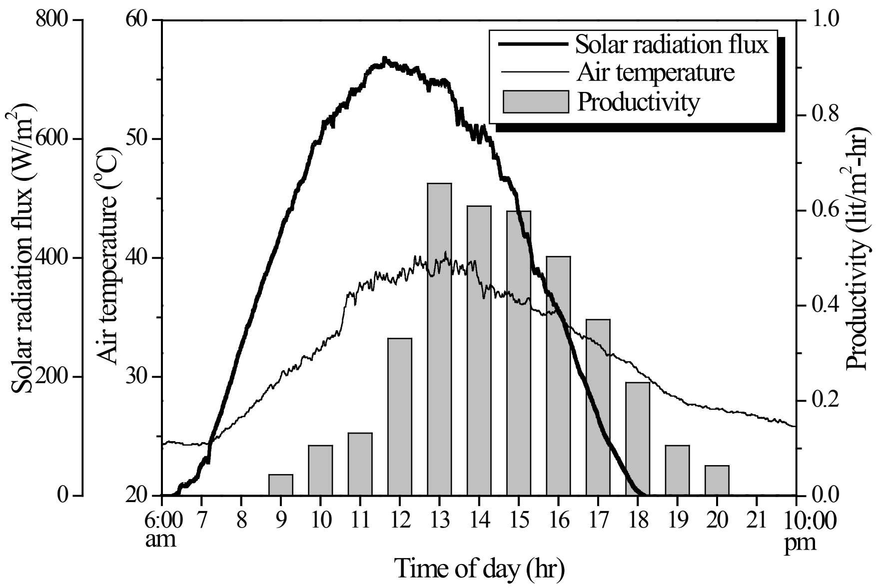


Figure 4 Observed diurnal variations of ambient air temperature, radiation flux and production fluxes for the TSS at KUET, Khulna for March 18 of 2010.

Figure 5 shows the variations of the observed daily distillate production rates from January to April of 2008, 2009, 2010 and 2011. The average production rates are estimated as 1.70, 2.60, 3.20 and 2.50 lit/m^2-day for the month January, February, March and April, respectively. One year basis field work on the TSS has been carried out from October 2009 to September 2010 and average daily productions for each months are calculated and tablated in Table 1. For calculating the average daily production, non-sunshine days and remarkable very low-sunshine days due to cloud, rain etc. are not considered in the calculation.

Figure 6 shows the variations of the maximum daily production per unit saline water surface in the trough for the TSS for all 12 months in the year 2010. It is seen from the figure that the production is minimum in December-January (1.8–2.0 lit/m^2-day) and then increased radpidly, peaked between April–July (3.5–3.8 lit/m^2-day) and then declined gradually. The highest maximum daily production is observed in April as 3.81 and lowest in January as 1.79 lit/m^2-day. The average maximum daily production for a month is 3.03 lit/m^2-day. The correlation for the maximum daily production rate in any month in a year can be expressed by the regression equaion given below.

$$y = 0.967 - 1.168x - 0.145x^2 + 0.005x^3 \qquad (r^2 = 0.89) \tag{1}$$

where, y = maximum daily production rate in any month (lit/m^2-day)
x = rank for the month (1 for January, 2 for February and so on)

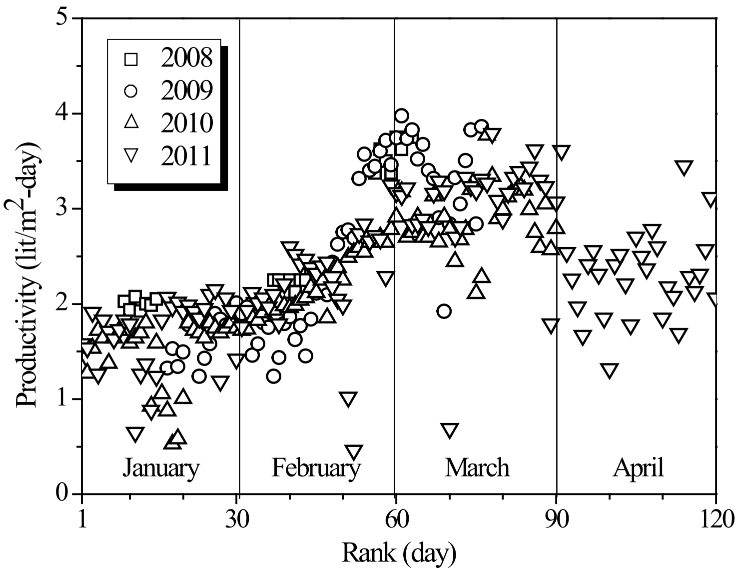


Figure 5 Variations of the observed daily distillate production rates for the TSS at KUET, Khulna from January to April of 2008, 2009, 2010 and 2011

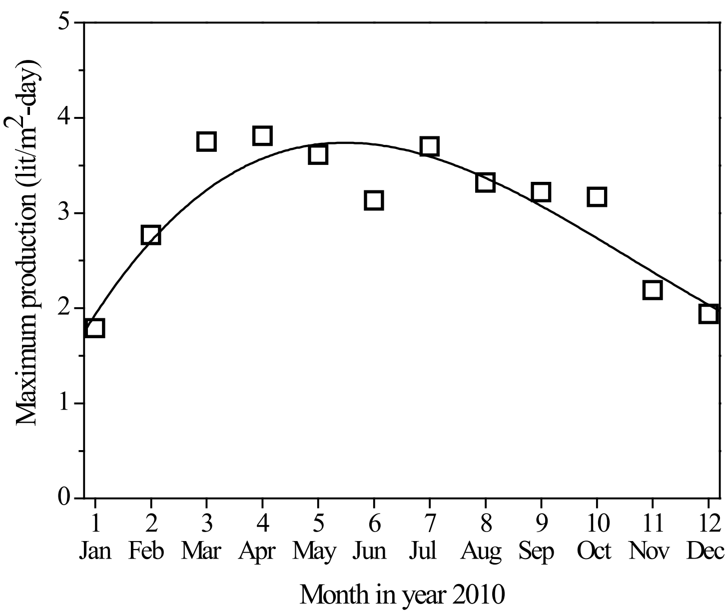


Figure 6 Maximum daily production for the TSS for all 12 months throughout the year 2010.

Table 1 Average daily production rate for all twelve months for the TSS in the year 2010

January	February	March	April	May	June	July	August	September	October	November	December
1.79	2.77	3.75	3.81	3.61	3.13	3.70	3.32	3.22	3.17	2.19	1.94

6. COST ESTIMATION

The initial cost of each tubular solar still was found as Tk. 80.00 and the total cost throughout the design life is estimated as Tk. 110.00. Table 2 shows the cost estimation of tubular solar still. Production cost of water from the TSS is estimated as 0.38 Tk./lit. The production cost is calculated as follows.

The average daily production for a month	= 3.03 lit/m^2-day	= 0.485 lit/day
Assume average daily production throughout a year	= 0.80 × 0.485	= 0.388 lit/day
Assume design life of a TSS	= 2 year	
The production of water in the design life	= 0.388×2×365	= 283.2 lit
Production cost of water	= 110 /283.2	= 0.39 Tk./lit

Table 2 Cost estimation of tubular solar still (Design life = 2 years)

SL. No.	Item Description	Amount in Tk.
1	G. I. wire to make the tubular frame	30
2	Trough preparation	10
3	Polythene to cover the tubular frame as condensation surface	15
4	Wooden frame to support the TSS	15
5	Miscellaneous	10
	Initial Cost =	**80**
6	Maintenance cost throughout design life (lump sum)	30
	Total Cost =	**110**

7. DISCUSSIONS AND CONCLUSIONS

The production rate of a solar stills is mainly depends on the intensity of solar radiation and the production rate is higher in the summer season. The TSS is constructed using locally available material and the construction is very simple. Also, the operation and maintenance of a TSS is very simple and easy. It could open easily to clean the trough or to remove the accumulated brine and to feed the saline water in the trough. The average daily production rate for the TSS is found as 3.03 lit/m^2-day, with highest and lowest values are 3.81 and 1.79, respectively. Highest productions are observed in April-June and lowest are December-January. Initial cost for the construction of the TSS is found as 80 Tk./TSS and water production cost is estimated as 0.39 Tk./lit.

The result presented in this study gives clear information to understand the behavior of production rate and other related informations for the TSS. The application of this process can fulfill the demand of fresh water for drinking purpose for single household effectively. It is concluded that due to low initial cost and also easier construction, operation and maintenance of TSS than BSS, one can easily use a TSS for drinking and other purposes in remote, coastal and arid areas or in an emergency to meet small scale fresh water demand.

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PHYSICAL MODEL STUDIES TO SUPPORT THE DESIGN OF MAIN SPILLWAY OF THE PROPOSED GANGES BARRAGE

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ABSTRACT

A barrage across the Ganges River at Pangsha has been proposed by feasibility consultants to store water and augment dry season flow into the distributaries of the Ganges. The waterway width (1728m) of the barrage consists of main spillway and undersluice bays, fish passes, navigation lock and hydro-power station. River Research Institute (RRI) has conducted detail model study for main spillway to support its design in terms of afflux, discharge co-efficient, water surface profile, scour profile downstream of the stilling basin with and without block protection under submerged unregulated flow conditions and nature of flow in the stilling basin under regulated flow conditions. The scale ratio of the model is set as 1:24. The model has been constructed in a straight flume. The barrage section reproduced in the model consists of one full bay (18m), two piers of 2.5m width and half of the portion of bays on the other side of each pier. The flume width is 1.71m. The stage-discharge curve established for the barrage site has been used to conduct model investigations. This paper presents the experimental results of design alternatives of main spillway and stilling basin and discusses the results in terms of their reliability and effectiveness. It is revealed that the design of main spillway is appropriate and the low Froude number basin works well to stabilize the hydraulic jump within the stilling basin.

Keywords: *Afflux, Barrage, Froude Number, Hydraulic Jump, Main Spillway, Stilling Basin*

1. INTRODUCTION

The construction of the proposed Ganges barrage is of immense importance for effective utilization of the Bangladesh share of Ganges flow and for the benefit of the people living in the Ganges Dependent Area. The layout of barrage is shown in Figure 1. Physical model studies are being conducted in RRI to support the Feasibility Study and Detailed Engineering for Ganges Barrage Project. The maximum waterway width of 1728m is established by model studies. The total spillways and undersluices length has been taken as 1620 m, corresponding with 78 spillway bays and 18 undersluice bays with 18 m wide openings.

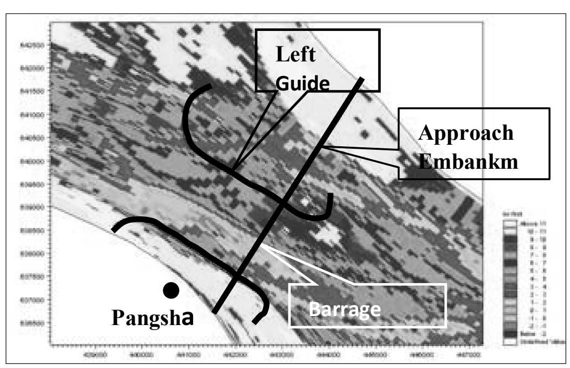

Figure 1 Layout of the proposed Ganges barrage at Pangsha

The main spillway is an important component of a barrage. Physical model studies play a vital role in planning and design of hydraulic structures like main spillway. Design of hydraulic structures is generally refined on the basis of detail physical model studies. The principal features and dimensions of the proposed Ganges barrage have been designed by the detailed engineering consultants on the basis of physical overall model and numerical

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model investigation results. The detail model for main spillway mainly aims to determine the afflux, surface water profile, discharge co-efficient etc. under different submerged unregulated flow conditions and to observe the hydraulic performance of stilling basin as designed and to suggest the modification of stilling basin if any for better performance in gated conditions. Appropriate scale between model and prototype structure plays imperative role in terms of rationality and reliability of the model results. This type of models gives best results if undistorted because of three-dimensional nature of flow pattern. Such undistorted models are also well fit for study of scour and stability of scour protection, which in many cases are an integral part of the local studies. The main spillway is the main body of the proposed Ganges barrage, normal RCC slab that supports the steel gate. The section of the main spillway is shown in Figure 2.

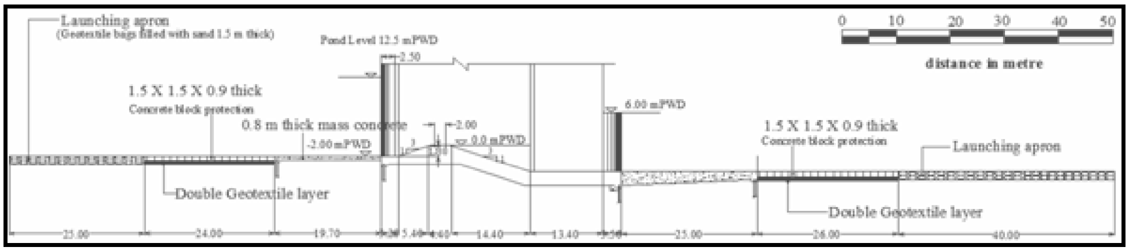

Figure 2 Section of main spillway (RRI, 2011)

The section of the main spillway consists of upstream concrete floor at elevation -2 mPWD, crest at elevation 0 mPWD, upstream slope (3:1), downstream slope (3:1) and downstream concrete floor at elevation -5 mPWD. There are also upstream sheet piles, downstream sheet piles, intermediate sheet piles and concrete block protection and launching apron both upstream and downstream.

The scale ratio of the model is set as 1:24. The model has been constructed in a straight flume using indoor modelling facilities of RRI. The barrage section reproduced in the model consists of one full bay, two piers of 2.5m width and half of the portion of bays on the other side of each pier. The flume width is 1.71m for the selected scale ratio. The test section of the model is constructed in this flume one side of which is fitted with steel sheet and the other side with transparent plastic panels to facilitate visual observations inside the flume. The radial gate, cement concrete blocks and loose protection works have been fabricated in the model as per design.

Detail model investigations for main spillway have been conducted with some specific objectives in view. Five test series have been conducted for determination of the needed information in unregulated and gated conditions for different discharges.

The information derived for unregulated submerged flow conditions are (i) water surface profiles (ii) discharge co-efficient (iii) reduction of discharge co-efficient with submergence with and without basin elements in place and (iv) water surface profiles and scour profiles downstream of the stilling basin with and without block protection and launching apron in place. The information derived for gated conditions are the nature of the hydraulic jump and the position and depth of maximum scour downstream for a critical downstream release condition with alternative designs of stilling basin in place. The other tests in gated conditions are yet to be conducted. Some findings of the model study have been presented in this paper.

2. METHODOLOGY

2.1 Model Design

The model for main spillway has been constructed using RRI indoor modelling facilities. The model has been designed to accommodate a short section of the main spillway. In the model the prototype situation has been replicated in a flume on a scale ratio of 1:24. The model is undistorted and the geometric scale is selected based on the available laboratory space, pumping capacity, measurements, dimension of the structure, governing processes to be simulated and scale conditions to be fulfilled. With this scale the model is of sufficient size that surface tension is minimized and that surface resistance is not greatly out of scale. In order to reproduce water flow and scour downstream of the structure following scale conditions are to be fulfilled (Sharpe, 1981).

i. Geometric Condition

The geometric condition is important to be fulfilled in order to diminish scale effects related to the three dimensional flow. The geometric condition is fulfilled when the length scale is equal to the depth scale i.e.

$L_r = h_r$..........(1)

Where, L_r = length scale and h_r = depth scale

ii. Roughness Condition

In an undistorted model the roughness condition is fulfilled when the scale of the Chezy roughness is equal to 1 or when the water slope in the model is equal to the water surface slope in prototype *i.e.*

$C_r^2 = L_r / h_r = 1$..........(2)

Where, C_r = roughness scale

iii. Froude Condition

The Froude condition is important to have a dynamic similarity for free surface flow with respect to the influence of gravity. The Froude condition is fulfilled when

$V_r = L_r^{0.5} = h_r^{0.5}$ $(L_r = h_r)$..........(3)

The discharge scale for the undistorted model can be determined from

$Q_r = L_r^{2.5} = h_r^{2.5}$..........(4)

iv. Transport Intensity

One of the main objectives of the model study is to determine scour downstream of the structure under different discharges. The following scale condition has to be satisfied for reproduction of the transport intensity when most of the sediment in the prototype is transported as suspended load.

$V_r = C_r D_r^2 \Delta_r$..........(5)

Where, V_r = velocity scale
C_r = roughness scale
D_r = diameter scale and
Δ_r = relative density scale

The above scale condition has led to the selection of appropriate d_{50} of the model bed sand so that the velocity scale needed for fair reproduction of the transport intensity in the model almost corresponds to the velocity scale according to Froudian law of similitude. The relationship of dimension and hydraulic quantities between model and prototype, which is based on Froudian law is given in Table 1.

Table 1 Relationship of dimensions and hydraulic quantities between model and prototype

Parameters	Unit	Scale
Length (*L*)	m	24
Depth (*h*)	m	24
Velocity (*V*)	m/s	4.9
Discharge (*Q*)	m^3/s	2822
Time (*T*)	s	4.9
Froude number (*Fr*)	-	1
Roughness co-efficient (*n*)	$m^{-1/3}s$	1.7