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Nomenclature

G = Air mass velocity through the bed(kg/m^{2}s)

α = *Solar* absorptance

τ = *Solar* transmittance

t = time

m = mass (kg)

$\dot{m}$ = mass flow rate of air (kg/s)

T = *Temperature* (K)

h = heat transfer coefficient(W/m^2K)

W = Width of the solar collector(m)

$TT = Trinidad and Tobago Dollars

subscript:

a = ambient

ab = absorber

p = plate

r = radiative

c/ct = concrete/copper tube

s = solar

conv = convective

g = glazing

fa = air above absorber

fb = air below absorber

I. Introduction

Energy economics is a specialized field used to make decisions on energy purchases, selection of competing energy generation technologies, and financing of energy technologies. A thorough study of this subject is beyond the scope of this research, but every engineer should have a basic understanding of energy economics in order to bridge the gap between engineering decision analysis and economic decision analysis. The most efficient energy conversion technology may not be the most cost effective.

Any economic-based decision on energy or energy technology will include some type of analysis involving capital and recurring costs. The scope of the analysis can vary significantly. The particular choice of analysis will depend on the desired basis for comparison. Typically, these various analysis methods are subsets of three general methods [1]:

1. Determine largest possible savings in energy costs for a fixed budget;
2. Determine the minimum budget required to achieve a specified reduction in energy costs or utilization; and
3. Determine return-on-investment for an alternative energy system.

The type of analysis chosen has much to do with type of energy project being considered. For instance, a short-lived project will not be affected by the future value of money, but a project which is expected to take decades will certainly be affected by future costs. The cost effectiveness of the short-lived project may be

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accomplished using a simple payback method. The long-lived project may be better assessed through a life cycle analysis (LCA). Simple Payback Method determines the time period to recover capital costs. Typical considerations are[2]:

i. Accumulation of savings
ii. No future value of money
iii. No interest on debt
iv. No comparison to fuel costs

The Simple Payback Method penalizes projects with long life potentials in part because any savings beyond payback period are ignored. There is no accounting for inflation or for escalation of future savings in fuel costs that historically have increased at a faster rate than inflation.

Life Cycle Analysis, once called Engineering Economic Analysis, considers the total cost over anticipated useful life, where useful life is the lesser of lifetime or obsolescence. Analysis may include: Capital costs, operating costs, maintenance costs and contracts, interest on investment, fuel cost, salaries, insurance, salvage value and taxes.

Life Cycle Analysis (LCA) may account for all costs including indirect costs paid by society but not reflected as cash flow. An example would be health and environmental costs associated with pollution due to electric power generation from coal; a cost not directly paid by the power generating utility. The difficulty with life cycle analysis is that many of the costs are in the future and can only be estimated with some unknown uncertainty. New technologies may also result in unanticipated obsolescence that, in hindsight, will turn a `cost effective' decision into an investment loss.

For the purposes here, Life Cycle Analysis encompasses many variations. All of the economic evaluation analysis methods are attempting to do two things. The first is to manipulate costs and savings in time to some common basis. The second is to assess these costs against some comparative objective; i.e., (i) which energy system has the lowest total expense, (ii) which system maximized return on investment, (iii) which system will maximize savings in energy costs. Some common evaluation methods [3]are:

1. Life-Cycle Cost Method (LCC): all future costs are brought to present values for a comparison to a base case. The base case may be a conventional energy system, design variations in alternative energy systems, or the alternative of not making the investment. LCC is commonly used to determine the `cost- minimizing' option.
2. Levelized Cost of Energy (LCOE): seeks to convert all costs (capital and recurring) to a value per energy unit that must be collected (or saved) to ensure expenses are met and reasonable profits collected. Future revenues are discounted at a rate that equals the rate of return that might be gained on an investment of similar risk; often called the `opportunity cost of capital'. LCOE is often used to compare competing energy producing technologies.
3. Net Present Value (NPV): (also known as Net Benefits, Net Present Worth, Net Savings Methods) determines the difference between benefits and expenses with everything discounted to present value. NPV is used for determining long-term profitability.
4. Benefit-to-Cost Ratio (BCR): (also known as Savings-to-Investment Ratio) is similar to NPV, but utilizes a ratio instead of a difference. Benefits usually imply savings in energy cost. What to include in the numerator (benefits) and denominator (costs) varies and care should be taken when assessing a reported benefit-to-cost ratio. This method is often used when setting priorities amongst competing projects with a limited budget. Projects with the largest ratio get the highest priority.
5. Overall Rate-of-Return (ORR): determines the discount rate for which savings in energy costs are equal to total expenditures. This is equivalent to determining the discount rate that results in a zero NPV. Previous methods require a specifying a discount rate; this method solves for the discount rate. This method enables cash flow to be expressed in terms of the future value at the end of the analysis period.
6. Discounted Payback Method (DPM): determines the time period required to offset the initial investment (capital cost) by energy savings or benefits.

Unlike the simple payback method, the time value of money is considered. DPM is often used when the useful life of the project or technology is not known.

The performance of the concrete bed storage system is influenced by various design and operational parameters such as size and configuration of the concrete, size of bed, air mass flow rate,void fraction within the bed, thermal and physical properties of concrete, and inlet temperature of air.

For efficient applications, many scientists have studied the performance and approximate designing methods of packed bed energy storage system. Clark and Beasley [4] have developed one and two dimensional numerical models for the dynamic response of both fluid and solid temperatures in a packed bed and have studied the effects of void fraction, flow distribution, wall heat capacity, and wall energy losses on the dynamic response of the packed bed subjected to an arbitrary time dependent inlet and initial temperatures. Clark and Nabozny [5] also developed a computer program for formulating the dynamic response and thermal storage capacity of a packed bed storage unit for both charging and recovery modes. Saez and McCoy [6] model includes axial thermal dispersion as well as intra particle conduction. Rao and Suri [7] investigated both analytical and theoretical unsteady state heat transfer through packed bed storage of homogenous spheres. Chandra and Willits [8] conducted an experimental study and concluded that pressure drop is affected by rock size, bed porosity, and air flow rate. They also discovered that volumetric heat transfer coefficient depend only on rock size and air flow rate.

This study carried out the economic analysis of combined packed bed storage and solar collector system using the present value methods which can be used to bring all future costs, which may occur in different years, back to today's value of money. In this way, the cost effectiveness of different energy technologies can be compared on an equal basis.

II. Methodology

a) Theoretical Analyses of the Combined Packed Bed Storage and Solar Collector System

Figure 1.0 shows the schematic of the combined packed bed energy storage system and solar collector system.The size of the duct was 3 x 0.5 x 0.0254m. The packed bed storage system consists of packed spherical shaped concrete imbedded with copper tubes, an inlet plenum chamber and outlet plenum chamber. The copper tube was of type L and of 0.00635m standard size. The outside diameter of the copper tube was 0.02223m, the inside diameter was 0.01994m, wall thickness of 0.01143m, length 1.32m, number of copper tubes were 4 of two passes with radius 0.115m. The spherical shaped concrete was made of ratio 1:1.2:1.1 of cement, sand and gravel, respectively. Storage tank having 0.70 m diameter was made of MS sheet of 3.00 mm thickness. The tank was 1.07 m high, including lower and upper plenums of height 0.25 m each resulting to packed bed height of 0.47 m. Tank was insulated with fiber glass to minimize the heat losses.

The entry and exit lengths were 0.65 and 0.96m respectively, including the inlet plenum and outlet plenum height of 0.3 m each.

The solar air heater (SAH) has (1.90 x 0.80 x 0.1 m3) outer dimensions. The top of the SAH was covered with a single transparent glass layer. High transmissivityto solar radiation glass cover of 0.005m thickness. The gap spacing between the absorber plate and the glass cover is about 0.05m. The air heater frame was constructed from wooden plate of 0.012m thickness except at the bottom which has 0.019m thickness. The absorber plate which is made of aluminum plate having 0.0015m thickness was painted with matt black layer to increase the absorptivity of the solar radiation and thereby reduces the temperature gradient between the inside and outside surfaces. The air was heated while passing between the transparent glass cover and absorber plate. The system was insulated from all sides and bottom by a 0.05m thickness fine wood frame to reduce the heat losses to ambient air. The whole air heater was oriented to face south and tilted 100 with respect to the horizontal to maximize the solar radiation incident on the air heater.

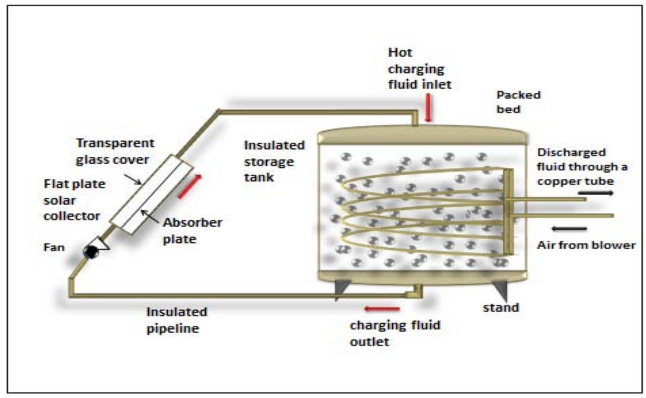

Figure 1.0 : Schematic of Combined Packed Bed Energy Storage and Solar Collector System

Therefore, the design of the concrete bed in this study has been made for the above design and operational parameters of combined packed bed energy storage system and solar collector system.

III. Daily Energy Stored in the Packed Bed

The energy balance equations for different components of the solar collector air heater and the packed bed energy storage system and their initial and boundary conditions are given below [9].

a) Solar Collector Air Heater

$$m_g C_g \frac{\partial T_g}{\partial t} = \alpha_g H + h_{r,ab,g}\left(T_{ab} - T_g\right) - h_{conv,g,fa}\left(T_g - T_{fa}\right) - h_{g,a}\left(T_g - T_a\right) \quad (1)$$

$$m_{fa} C_{fa} \frac{\partial T_{fa}}{\partial t} + \left(\frac{\dot{m}}{W}\right) C_{fa} \frac{\partial T_{fa}}{\partial x} = h_{conv,ab,fa}\left(T_{ab} - T_{fa}\right) + h_{conv,g,fa}\left(T_g - T_{fa}\right) \quad (2)$$

$$m_{ab}C_{ab}\frac{\partial T_{ab}}{\partial t}=\tau_g\alpha_{ab}H-h_{r,g,ab}\left(T_{ab}-T_g\right)-h_{conv,ab,fa}\left(T_{ab}-T_{fa}\right)-$$
$$h_{r,ab,p}\left(T_{ab}-T_p\right)-h_{conv,ab,fb}\left(T_{ab}-T_{fb}\right) \quad (3)$$

$$m_{fb}C_{fb}\frac{\partial T_{fb}}{\partial t}+\left(\frac{\dot{m}}{W}\right)C_{fb}\frac{\partial T_{fb}}{\partial x}=h_{conv,ab,fb}\left(T_{ab}-T_{fb}\right)-$$
$$h_{conv,p,fb}\left(T_{fb}-T_p\right) \quad (4)$$

$$m_pC_p\frac{\partial T_p}{\partial t}=h_{r,ab,p}\left(T_{ab}-T_p\right)+h_{conv,p,fb}\left(T_{fb}-T_p\right)-U_r\left(T_p-T_a\right) \quad (5)$$

b) Packed Bed

$$\rho_fC_f\varepsilon\frac{\partial T_f}{\partial t}+GC_f\frac{\partial T_f}{\partial x}=h_{Vf(c/ct)}\left(T_{c/ct}-T_f\right) \quad (6)$$

$$\rho_{c/ct}C_{c/ct}\left(1-\varepsilon\right)\frac{\partial T_{c/ct}}{\partial t}=h_{Vf(c/ct)}\left(T_f-T_{c/ct}\right) \quad (7)$$

c) Initial and boundary conditions

$$T_f\left(x,0\right)=T_{fi}=T_a\left(1\right)\text{ and }T_b\left(x,0\right)=T_b=T_{ia}\left(1\right) \quad (8)$$

$$T_{fa}\left(x,0\right)=T_{fb}\left(x,0\right)=T_a\left(1\right)\text{ and}$$
$$T_{ab}\left(x,0\right)=T_p\left(x,0\right)T_g\left(x,0\right)=T_a\left(1\right) \quad (9)$$

$$T_{fa}\left(0,t\right)=T_a=\text{inlet temperture for solar air heater,}$$
$$\text{if }\left[T_b\left(F_L,t\right)<T_a\right] \quad (10)$$

Where, F_L is the flow length

$$T_{fa}\left(L,t\right)=T_{fb}\left(0,t\right)$$
$$T_{fb}\left(L,t\right)=T_{fo}=\text{outlet air temperture for solar air heater for the bed.} \quad (11)$$

The temperatures of the air T_f and solids T_b within the packed bed at different locations and times were calculated by solving the above equations which use the finite difference method.

The daily energy stored $Q_s\left(KWh\right)$ was calculated as follows:

$$Q_s=\frac{\sum_{i=0}^{n-1}\left[\frac{\left\{T_b\left(i\right)+T_b\left(i+1\right)\right\}}{2}-T_a\left(1\right)\right]}{n\left(3.6\times10^6\right)}m_bC_bA_b \quad (12)$$

Where, $T_b\left(i\right)$ is the packed bed temperature at the ith zone and n is the number of zones.

The radiative $h_{r,ab,g}$ and $h_{r,ab,p}$, wind related convective $\left(h_{g,a}\right)$ and conductive $\left(U_r\right)$ heat transfer coefficients were calculated by using the standard heat transfer relations summarized in [10]. The forced convective heat transfer coefficients for the air heater $h_{conv,g,fa}$, $h_{conv,ab,fa}$, $h_{conv,ab,fb}$, and $h_{conv,p,fb}$, were calculated by using the relation derived by Tan and Charters [11]. The heat transfer coefficient between air and concrete and copper tube in the bed $\left(h_{Vf(c/ct)}\right)$ were computed by using the Coutier and Farber [12] relation which can be written as follows.

$$h_{Vf(c/ct)} = 700\left(\frac{G}{D_{c/ct}}\right)^{0.76} \quad (13)$$

IV. Daily Cost of the Storage System (DC)

In order to calculate the daily cost (DC) of the packed bed solar thermal energy storage system together with the solar air heater device, the different cost factors were calculated as given below [9].

a) *Daily blower cost (DBC)*

$$DBC = \frac{0.746\left(\dot{m}\Delta p c_{KW/h} h\right)}{\eta_m} \quad (14)$$

$c_{KW/h}$ = cost of electricity in KW/h

η_m = Electric motor efficiency

The pressure drop Δp can be determined using the relation:

$$\Delta p = f\left(\frac{F_L}{D_{c/ct}}\right)\left(\frac{G^2}{\rho_f}\right)\left(\frac{1-\varepsilon}{\varepsilon^3}\right) \quad (15)$$

$$\text{friction factor } (f) = \frac{150(1-\varepsilon)}{R+1.75} \quad (16)$$

$$R = \frac{GD_{c/ct}}{\mu} \quad (17)$$

b) *Daily capital cost of the bed and the solar air heater devices (DCC)*

$$DCC = CR\left(\frac{CI}{300}\right) \quad (18)$$

Where, Capital recovery (CR)

$$CR = \left[\frac{(CI - SV)}{SPWF}\right] + SV \times i \quad (19)$$

$SPWF$ = Series present forth factor (Table 1.0)

$$\text{Capital investment or first cost of the solar system } (CI) = \text{Material cost + Blower cost + Paint cost + Fabrication cost} \quad (20)$$

$$\text{Salvage Value } (SV) = 0.1(CI) \quad (21)$$

Daily Salvage Value (DSV)

$$(DSV) = \frac{(SFF)(SV)}{300} \quad (22)$$

$$\text{Where, Salvage Fund Factor } (SFF) = \frac{i}{\left[(i+1)^n - 1\right]} \quad (23)$$

i = interest rate rapid on borrowed, earned or saved money

c) *The Daily Maintenance Cost (DMC)*

The daily maintenance cost of the packed bed storage and the solar air heater device were considered to be 10% of the daily capital cost (DCC) of the system.

The Daily Cost (DC) of the system was then calculated and presented as shown in Figure 3.0.

Table 1.0 : Series Present worth Factors (SPWF).Factors for computing annual cost of investment over "N" years of life at the interest rates shown [2]

				Interest rate					
N	**6%**	**8%**	**10%**	**12%**	**14%**	**16%**	**18%**	**20%**	**N**
1	**0.943**	**0.926**	**0,909**	**0.893**	**0.877**	**0.862**	**0.847**	**0.833**	**1**
2	**1.833**	**1.783**	**1,736**	**1.690**	**1,647**	**1.605**	**1.566**	**1.528**	**2**
3	**2.673**	**2.577**	**2.487**	***2.402***	**2.322**	**2.246**	**2.174**	**2.106**	**3**

4	3.465	3.312	3.170	3.037	2.914	2.798	2.690	2.589	4
5	4.212	3.993	3.791	3.605	3.433	3.274	3.127	2.991	5
6	4.917	4.623	4.355	4.111	3.889	3.685	3.498	3.326	6
7	5.582	5.206	4.868	4.564	4.288	4.039	3.812	3.605	7
8	6.210	5.747	5.335	4.968	4.639	4.344	4.078	3.837	8
9	6.802	6.247	5.759	5.328	4.946	4.607	4.303	4.031	9
10	7.360	6.710	6.145	5.650	5.216	4.833	4.494	4.192	10
11	7.887	7.139	6.495	5.938	5.453	5.029	4.656	4.327	11
12	8.384	7.536	6.814	6.194	5.660	5.197	4.793	4.439	12
13	8.853	7.904	7.103	6.424	5.842	5.342	4.910	4.533	13
14	9.295	8.244	7.367	6.628	6.002	5.468	5.008	4.611	14
15	9.712	8.559	7.606	6.811	6.142	5.575	5.092	4.675	15
16	10.106	8.851	7.824	6.974	6.265	5.668	5.162	4.730	16
17	10.477	9.122	8.022	7.120	6.373	5.749	5.222	4.775	17
18	10.828	9.372	8.201	7.250	6.467	5.818	5.273	4.812	18
19	11.158	9.604	8.365	7.366	6.550	5.877	5.316	4.843	19
20	11.470	9.818	6.514	7.469	6.623	5.929	5.353	4.870	20

$$DC = DCC = DMC = DPC - DSV \quad (24)$$

V. Results and Discussions

For the numerical calculation the cost of absorbing paint was assumed as TT$ 7.0/m2, solar collector cover glass as TT$ 18.0/m2, air duct material as TT$ 23.0/m2, absorber plates as TT$ 19.0/m2, concrete materials as TT$ 44.0/m2 , fiberglass (insulation) as TT$ 12.0/m2 , wood as TT$ 15.0/m2 , and sheet metal as TT$ 45.0/m2. The cost of the blower is TT$ 650.0 and the cost of electricity as 27 cents. The rate of interest (i) was assumed as 10% and life of device (n) as 10 years. The fabrication cost was considered to be 25% of the capital investment. The operational time was considered as 300 days/year and 9 hours/day. Figures 78.0 and 79.0 shows the daily blower cost and daily cost of the entire packed bed storage system respectively as function of air flow rate for spherical shaped concrete of diameter 0.065m, 0.08m and 0.11m.

Spherical shaped concrete of size 0.065m diameter has the highest blower cost of $TT37.83/day at 0.045m3/s due to low porosity and high pressure drop while concrete size 0.11m diameter has the lowest blower cost of $TT0.16/day at 0.0094m3/s as shown in Figure 2.0.

Also, Spherical shaped concrete of size 0.065m diameter has the highest storage system daily cost of $TT38.83/day at 0.045m3/s while concrete size 0.11m diameter has the lowest daily cost of $TT1.16/day at 0.0094m3/s as shown in Figure 3.0.

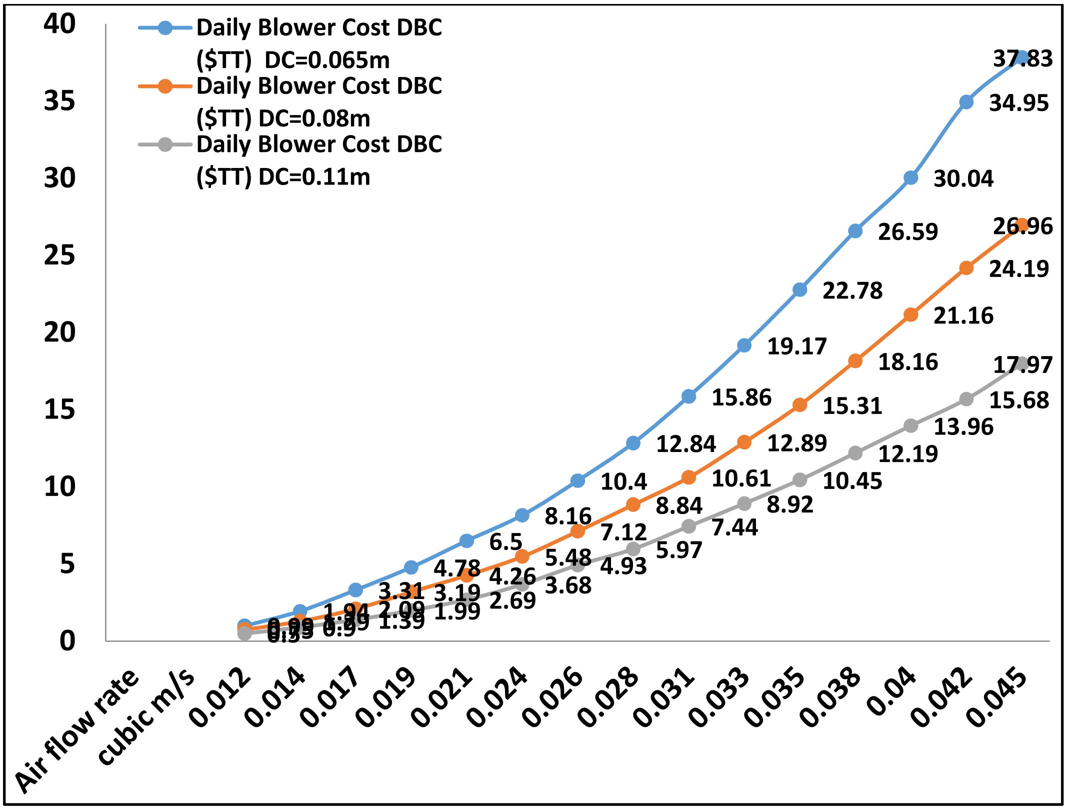

Figure 2.0 : Daily blower cost as function of air flow rate for different spherical shaped concrete of diameter 0.065, 0.08 and 0.11m

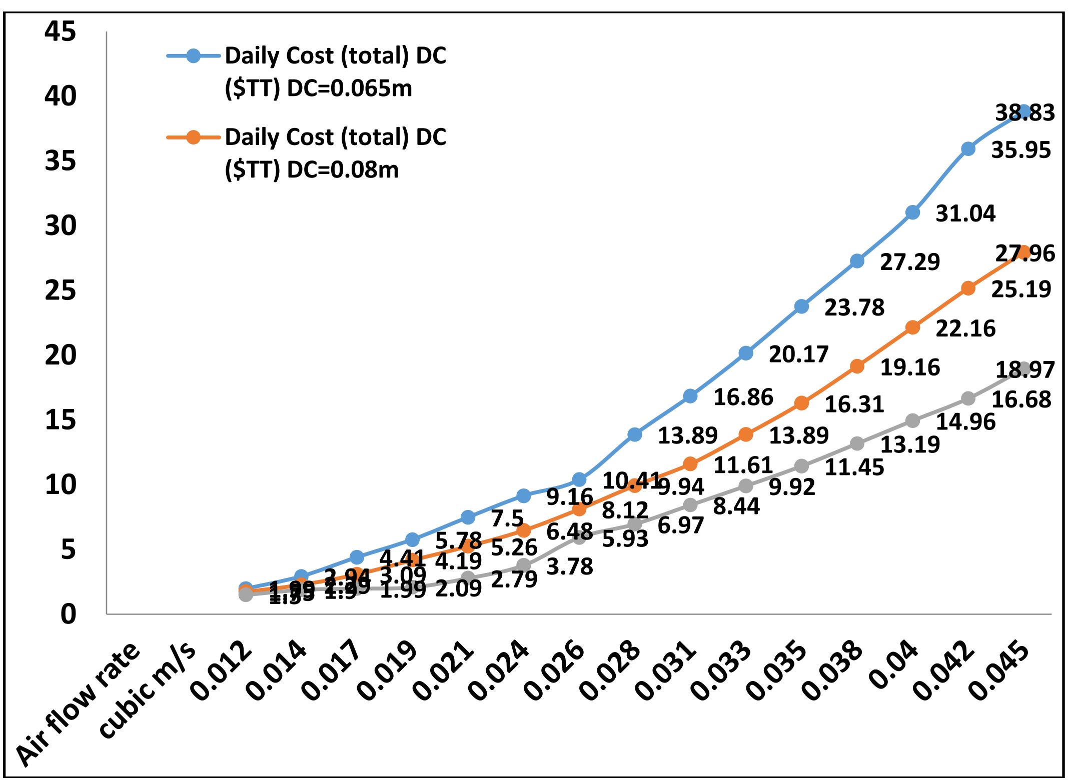

Figure 3.0 : Daily cost of the entire packed bed storage system as function of air flow rate for spherical shaped concrete of diameter 0.065, 0.08 and 0.11m

VI. Conclusion

The price of the combined packed bed energy storage and solar collector system needs to be determined, which allows the gross income calculation. Additional costs for the annual operation and maintenance was taken into account.

From the above discussion it was discovered that spherical shaped concrete of size 0.065m diameter has the highest blower cost of $TT37.83/day at 0.045m3/s due to low porosity and high pressure drop while concrete size 0.11m diameter has the lowest blower cost of $TT0.16/day at 0.0094m3/s. Also, spherical shaped concrete of size 0.065m diameter has the highest storage system daily cost of $TT38.83/day at 0.045m3/s while concrete size 0.11m diameter has the lowest daily cost of $TT1.16/day at 0.0094m3/s.

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