

Research Article

# Design, optimisation and system integration of low cost Ground Coupled Central Panel Cooling System (GC-CPCS )

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### Abstract

Photovoltaic(PV) cells also called Solar cells are electronic devices that convert sunlight directly into electricity. There are two prominent PV cell technologies viz. wafer-based crystalline silicon Solar cells and Thin Film Solar cells in the market today. The efficiency of wafer-based crystalline as well as Thin film Solar cells get reduced with increase of panel temperature. It is noted that the efficiency drops by about 0.4% for increase of 1° C of panel temperature. It is necessary to operate them at low temperatures to keep the PV module electrical efficiency at acceptable level. Therefore need for a low-cost cooling system for the Solar panels is felt. Air-cooling either by forced or natural flow, presents a non-expensive and simple method of PV cell cooling. This paper proposes schematic design, analytical design and optimisation of a Central Panel Cooling System (CPCS). Centralized design is useful in two respects viz. (i) it leads to low capital cost per watt output and (ii) it maximises the increase in output to the energy spent in the cooling system. This plant is being installed at Energy Park of Rajiv Gandhi Proudyogiki Vishwavidyalaya(RGPV), Bhopal, India.

**Keywords :** Efficiency of Solar panels, Panel Cooling System, Forced convection, Air conditioning systems, Ground-Coupled Heat Exchanger, Central Panel Cooling System(CPCS), Ground-Coupled Central Panel Cooling System (GC-CPCS)

### 1. Introduction

The operating temperature of a PV module has a direct influence on the performance.(Tang Y et al 2003) For example, the power output of a mono/poly-crystalline silicon module decreases at about 0.5%/°C. The variation of Efficiency vs Temperature is shown in Fig 1. ( Katkar A A et al 2011 )

The I-V curve of a PV device under illumination is a strong function of temperature. An illuminated PV cell converts only a small fraction (approx. less than 20%) of irradiance into electrical energy. The balance is converted into heat, resulting into heating of the cell. As a result, the cell operates above ambient temperature. Keeping insolation level as constant, if the temperature is increased, there is a marginal increase in the cell current but a marked reduction in cell voltage. An increase in temperature causes reduction in the band gap. This in turn causes some increase in photo-generation rate and thus, a marginal increase in current. However, the reverse saturation current increases rapidly with temperature. Due to this, the cell voltage decreases by approximately 2.2 mV per °C rise in its operating temperature, depending on

the resistivity of the silicon used: higher the silicon resistivity more marked is the temperature effect. (Khan B H 2006 )

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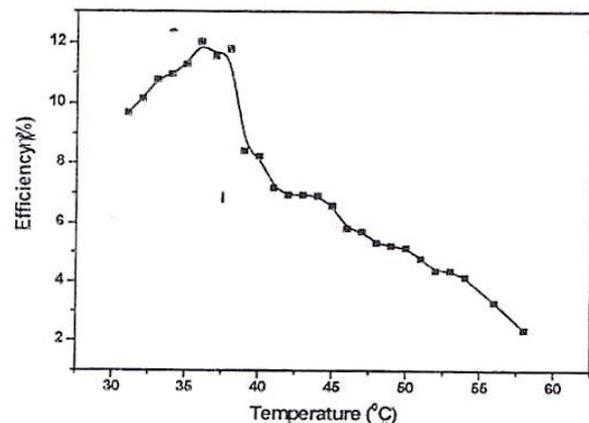


Fig 1 : Variation of Efficiency vs. Temperature

The objective of this project is to apply artificial cooling to PV modules and study the improvement in power output and find the optimum performance parameters.(Cruey Bryce et al 2006)

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## 2. Various Panel cooling technologies

It is well known that the efficiency of a PV solar cell decreases with the increase in operating temperature and cooling is beneficial. The various technologies for cooling of panels are discussed briefly.

**2.1 Hybrid PV-T systems:** Here fluid is run through the rear of the panels which absorb the heat. This concept offers an opportunity to increase overall efficiency by making use of waste heat generated in the PV module.

**2.2 Natural /Forced convection of air :** The transfer of heat between a solid boundary and moving air takes place by a combination of conduction and convection.

**2.3 Use of Heat Pipe:** Heat Pipe is a device for transferring heat from a source to sink by means of evaporation and condensation of a fluid in a sealed system.

**2.4 Heat Sink:** Fins are attached at the rear face of the panel.

**2.5 Mist sprays (Evaporative cooling) :** The Solar panels are cooled by spraying them with a mist of water.

**2.6 Water cooled chips:** In IBM's CPV system, water gushes through the base of Solar cells. It is similar to microprocessors with deep water coursing through micro-channels carved deep inside them.

## 3. Design considerations for Panel Cooling System

The design considerations for cooling of PV panels draws from the pioneer work by Royne . (Royne 2005). The following cooling and operational requirements are considered.

**3.1 Cell Temperature:** It is necessary to operate the PV Solar Panels at low temperatures to keep the panel electrical efficiency at acceptable level. (Tonui J K et al 2006) The system is designed to maintain the PV panel temperature within 30° - 40°C.

**3.2 Uniformity of temperature:** In a Photovoltaic module, a number of cells are electrically connected in series, and several of these series connections can be connected in parallel. When cells are connected in series, the cell that gives the smallest output will limit the current. This is known as *Current matching problem*. Because the cell efficiency decreases with increasing temperature, the cell at the highest temperature will limit the efficiency of the whole string. This problem can be avoided by keeping a uniform temperature across each series connection.

**3.3 Reliability & less maintenance cost:** Reliability is important aspect because failure of cooling system could lead to the destruction of PV cells. Further the design should be simple enough to keep maintenance cost to a minimum.

**3.4 Pumping power:** The power required to run the cooling system for active cooling is a parasitic loss. It has to be kept to a minimum. *Effectiveness* of panel cooling system can be defined as Increase in output to the energy spent to run the cooling system.

**3.5 Minimal capital cost:** Cost of raw materials, Blower cost, Fabrication cost should be kept down to keep the Capital cost of installation of Cooling system to a minimum. Here the parameter to monitor is *Capital cost per unit power output*. It can be defined as – Cost of installation of cooling system to total output (peak, Wp) of the system.

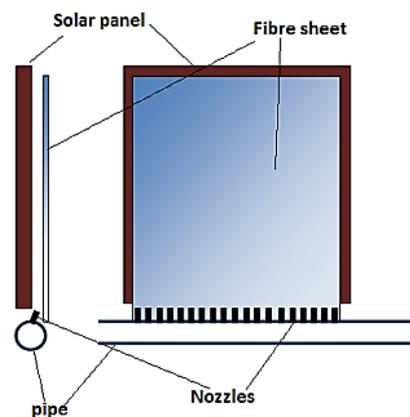
## 4. Proposed panel cooling method

The proposed method suffices to cool the Solar Panels by Forced Convection of ambient air driven by a blower. The blower is run by power provided by a separate and dedicated PV cell.

Air is passed through a ground-coupled heat exchanger to drop its temperature. The cooled air cools the Solar panels as it passes through the rear surface of the Solar Panels. To facilitate develop streamlines of flow, fibre sheets are placed towards the rear surface of the Solar panels. The air flows through the space between the fibre sheets and the rear surface of the Solar panels. (Fig 2) Natural convection is also possible in this set up.

There are nine Solar Panels of 100 W each. The air is driven by a single blower. This design is similar to Central cooling system. Hence the term *Central Panel cooling System (CPCS)*<sup>®</sup> is conceived.

The cooled air is distributed to each Solar Panels by means of a pipe. Nozzles are provided on the pipe through which the air comes out. Nozzles ensure streamlines are developed in the desired direction.



**Fig 2 :** Arrangement of Solar panel, Fibre sheet and nozzles

**4.1 Ground - Coupled heat exchanger /Earth Tubes:** A Ground-Coupled heat exchanger is an underground heat exchanger that can (a) capture heat from ground and/or (b) dissipate heat to the ground. They use the Earth's near

constant temperature to warm or cool air for residential or industrial use.

If building air is blown through Ground-Coupled heat exchanger for heat recovery ventilation they are called *Earth Tubes*. Earth Tubes are viable and economical alternative to conventional Central Cooling Systems since there are no compressors, chemicals or burners and only blowers are required to move the air. ([http://en.wikipedia.org/wiki/Ground-coupled\\_heat\\_exchanger](http://en.wikipedia.org/wiki/Ground-coupled_heat_exchanger))

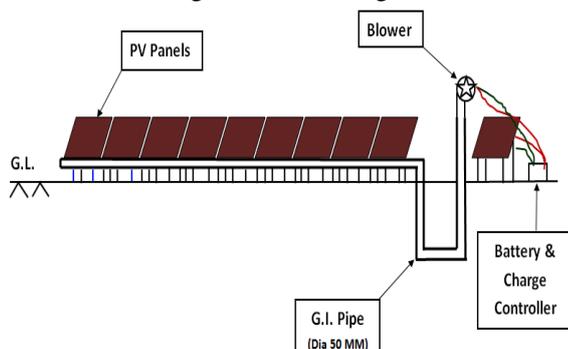
**4.2 Central Panel Cooling System (CPCS):** Here we draw analogy from the widely used Central Air Conditioning Systems. There are two broad categories of Air conditioning systems:

- (a) Centralised air conditioning systems
- (b) Decentralized air conditioning systems (Bhatia A)

*Centralised air conditioning systems* serve multiple spaces from one base location. *Decentralised air conditioning systems* typically serve single or small spaces from a location within or directly adjacent to the space.

*Central Panel Cooling System(CPCS)* is similar to Centralised air conditioning systems chilled water is used as a cooling medium.

The Central Panel Cooling System(CPCS) proposes to use cooled air, as the working fluid, which comes through the *ground coupled heat exchanger* which makes a *Ground-coupled Central Panel Cooling System (GC-CPCS)*. The schematic drawing is shown in Fig 3.



**Fig 3:** Schematic design of GC-CPCS



**Fig 4 :** Thin-Film PV panels at RGPV, Bhopal

This system is being installed at Thin-Film Solar PV panels at Energy Park of Rajiv Gandhi Proudhyogiki Vishwavidyalaya (RGPV), Bhopal, India. (Fig 4)

Specifications of this Solar PV system :

Make : Schott Solar

Type : Solar Thin Film Module, Single junction a-Si/CIGS Technology

Capacity : 920-960 W

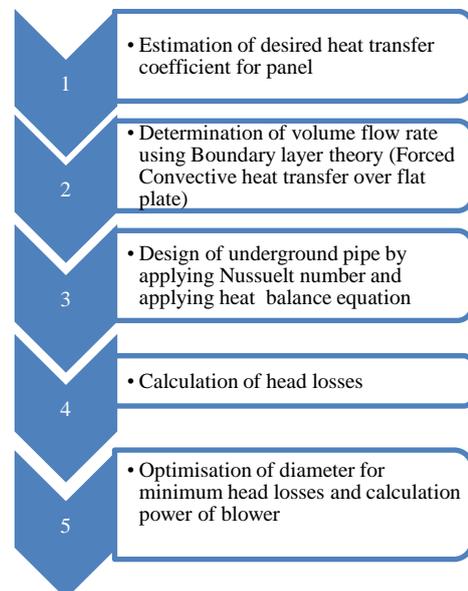
**4.3 Design advantage of GC-CPCS**

In Table 1 we discuss how GC-CPCS meets the design considerations laid down in Section 3.

**Table 1 :** Details on how GC-CPCS meets the design consideration

Design consideration	How GC-CPCS meets the design consideration
Cell temperature	The Solar panels are cooled by forced convection of underground cooled air
Uniformity of temperature	For every panels there are 20 nozzles
Reliability & less maintenance	Design is simple and requires less moving parts. This makes it reliable and it requires less maintenance
Pumping power	The Central Cooling concept allows use of blower economically. The power used by blower approximately 40 W is < 5% of the total power output of the system It is not economical to cool a single panel as blower consuming 8-10 W power is difficult to design
Minimal capital cost	Cost of fabrication, material, blower is distributed among 9 Solar Panels having output of 900 Wp. Thus Capital cost Per unit Output is reduced

**5. Analytical Design**



**Fig 5 :** Flow Chart for design of GC-CPCS

## Nomenclature

a: Cross-sectional area of nozzle (mm<sup>2</sup>)  
 A<sub>panel</sub>: Area of panel (m<sup>2</sup>)  
 A<sub>sur</sub>: Surface area of underground pipe (m<sup>2</sup>)  
 A<sub>pipe</sub>: Cross sectional area of pipe (m<sup>2</sup>)  
 C<sub>p</sub>: Specific heat (J/Kg-°C)  
 D: Diameter of pipe (mm)  
 f: Darcy Friction factor  
 g: Acceleration due to gravitation (m/s<sup>2</sup>)  
 h<sub>panel</sub>: Desired heat transfer coefficient of panel(W/m<sup>2</sup>-°C)  
 h<sub>pipe</sub>: Heat transfer coefficient of pipe (W/m<sup>2</sup>-°C)  
 H1: Exit head losses (m of air column)  
 H2: Loss of head due to viscous friction for pipe length without nozzles (m of air column)  
 H3: Loss of head due to viscous friction for pipe length having nozzles (m of air column)  
 H4: Head loss due to bends (m of air column)  
 H5: Head loss to maintain the flow (m of air column)  
 H6: Head loss at entry (m of air column)  
 H: Total head loss (m of air column)  
 K: Thermal conductivity of air (W/m-K)  
 K<sub>b</sub>: Loss coefficient due to bends  
 K<sub>e</sub>: Loss coefficient for losses at entry  
 K<sub>f</sub>: Loss coefficient due to fittings  
 l<sub>1</sub>: Pipe length without nozzles (m)  
 l<sub>2</sub>: Pipe length having nozzles (m)  
 L: Length of panel (m)  
 L<sub>pipe</sub>: Length of underground pipe (m)  
 ṁ<sub>T</sub>: Total mass flow rate (kg/s)  
 P: Pumping power required (W)  
 P<sub>blower</sub>: Power input to blower (W)  
 Pr: Prandtl number  
 Q: Energy loss as heat per panel (W)  
 q<sub>n</sub>: Volume flow rate per nozzle (m<sup>3</sup>/s)  
 q<sub>p</sub>: Volume flow rate per panel (m<sup>3</sup>/s)  
 q<sub>T</sub>: Total volume flow rate (m<sup>3</sup>/s)  
 Re<sub>D</sub>: Reynolds Number  
 T<sub>w</sub>: Wall temperature, °C, (under earth temp.)  
 T<sub>i</sub>: Inlet air temperature of underground pipe, °C  
 T<sub>o</sub>: Outlet air temperature of underground pipe, °C  
 T<sub>a</sub>: Ambient temperature, °C  
 T<sub>pavg</sub>: Average panel temperature, °C  
 U: Velocity of flow at exit of nozzle (m/s)  
 V: Velocity of flow in the pipe(m/s)  
 W: Width of panel (m)

### Greek symbols

Δt<sub>a</sub>: Average temperature difference between panel and ambient (°C)  
 μ: Absolute viscosity (N-s/m<sup>2</sup>)  
 ν: Kinematic viscosity (m<sup>2</sup>/s)  
 ρ: Density of air (kg/m<sup>3</sup>)  
 η<sub>o</sub>: Overall efficiency of blower

### 5.1 Estimation of desired heat transfer coefficient of panel

Peak output of one panel = 100 W<sub>p</sub>  
 Assuming 10% efficiency of panel incident Solar irradiance on one panel = 100/0.1 = 1000 W  
 Q = Energy lost as heat per panel (Khan B H 2004)  
 = 20% of incident Solar radiation  
 = 200 W

The flow over Solar panel is considered equivalent to flow over flat plate.

Ambient temperature, T<sub>a</sub>, is taken as 40°C and Panel temperature is taken as 60°C.

The system is designed to cool the panel to 40°C and cool the ambient air to 30°C in the underground heat exchanger i.e. T<sub>o</sub> = 30°C.

Average panel temperature, T<sub>pavg</sub> = (60 + 40)/2 = 50°C

Average temperature difference between panel and outlet temperature of air from the nozzle,  
 Δt<sub>a</sub> = T<sub>pavg</sub> - T<sub>o</sub> = 50 - 30 = 20°C

Surface area of panel,

$$A_{\text{panel}} = L \times W = 1.27 \text{ m} \times 1.27 \text{ m} = 1.6129 \text{ m}^2$$

Desired convective heat loss per panel,

= Energy lost as heat per panel

$$= Q = h_{\text{panel}} \times A_{\text{panel}} \times \Delta t_a$$

$$\Rightarrow h_{\text{panel}} = Q / A_{\text{panel}} \times \Delta t_a \\ = 200 / 1.6129 \times 20 \\ = 6.2 \text{ W/m}^2\text{-}^\circ\text{C} \quad (1)$$

5.2 Determination of volume flow rate using Boundary Layer Theory ( Forced Convective heat transfer over flat plate )

$$h_{\text{panel}} = 0.664 K Pr^{1/3} \sqrt{\frac{U}{\nu L}} \quad (\text{Arora S C et al2002}) \quad (2)$$

Length of panel, L = 1.27 m

Air properties at 40°C, the bulk mean temperature. (Kothandaraman C P et al 2010 )

K = 0.02576 W/m-K

Pr = 0.699

ν = 16.96 x 10<sup>-16</sup> m<sup>2</sup>/s

μ = 19.12 x 10<sup>-16</sup> N-s/m<sup>2</sup>

C<sub>p</sub> = 1005 J/Kg-K

From equations (1) and (2) we get the free stream velocity of flow for the panel which is also the velocity of flow at the exit of the nozzles.

$$U = 3.139 \text{ m/s} \quad (3)$$

Volume flow rate through one nozzle

$$q_n = U \times a$$

where 'a' is cross sectional area of the nozzle.

$$a = 6 \text{ mm} \times 2 \text{ mm} = 12 \text{ mm}^2$$

$$q_n = 3.139 \times 12 \times 10^{-6} = 3.7668 \times 10^{-5} \text{ m}^3/\text{s}$$

There are 20 nozzles per panel. Therefore Volume flow per panel,

$$q_p = q_n \times 20 = 3.7668 \times 10^{-5} \times 20 \\ = 7.5336 \times 10^{-4} \text{ m}^3/\text{s}$$

There are 9 panels. Therefore Total volume flow rate, q<sub>T</sub> = q<sub>p</sub> x 9 = 7.5336 x 10<sup>-4</sup> x 9

$$= 6.7802 \times 10^{-3} \text{ m}^3/\text{s} \quad (4)$$

Total mass flow rate,

$$\dot{m}_T = \rho \times q_T = 1.128 \times 6.7802 \times 10^{-3} \\ = 7.6481 \times 10^{-3} \text{ kg/s} \quad (5)$$

### 5.3 Design of underground pipe ( heat exchanger )

The ambient temperature is taken as 40°C. The system is designed to reduce the temperature of ambient air to 30°C in the underground pipe.

The main parameters to be calculated are

- (i) Diameter of pipe
- (ii) Length of underground pipe
- (iii) Total Head losses

We assume, Diameter of pipe, D=20 mm, for first iteration.

$$Re_D = 4 \times \dot{m}_T / \pi \times D \times \mu$$

$$Re_D = 4 \times 7.6481 \times 10^{-3} / (\pi \times 0.02 \times 19.12 \times 10^{-6})$$

$$= 25465$$

$$Re_D > 2300 \quad (\text{Kothandaraman C P et al 2010})$$

Hence the flow is turbulent

Now, using Dittus-Boelter equation, (Kothandaraman C P et al 2010)

$$Nu = 0.023 Re_D^{0.8} Pr^{0.3}$$

$$= 0.023 \times 25465^{0.8} \times (0.699)^{0.3}$$

$$= 69.1553$$

But,  $Nu = h_{pipe} D / K$

$$h_{pipe} \times 0.02 / 0.02576 = 69.1553$$

$$h_{pipe} = 95.2960$$

$$A_{sur} = \pi \times D \times L_{pipe}$$

$$= \pi \times 0.02 \times L_{pipe} / 1000$$

$$= 0.06283 L_{pipe}$$

Heat balance equation, (Arora S C et al 2002)

$$h_{pipe} A_{sur} [(T_i + T_o) / 2 - T_w]$$

$$= \dot{m}_T C_p (T_i - T_o)$$

$T_w = 29^\circ\text{C}$  (under earth temperature for Bhopal)

$T_o = 30^\circ\text{C}$

$T_i = T_a = 40^\circ\text{C}$

From equations, 5, 8, 9 and 10

Length of underground pipe

$$L_{pipe} = 2.14 \text{ m}$$

#### 5.4 Calculation of head losses

The head losses will the pumping power required to run the system. The various head losses are given below.

##### 5.4.1 Exit head loss, H1

$$\text{Exit loss for one nozzle} = U^2 / (2 \times g)$$

$$\text{Number of nozzles} = 180$$

Total exit loss

$$H1 = U^2 / (2 \times g) \times 180$$

$$= (3.139)^2 / (2 \times 9.81) \times 180$$

$$= 90.397 \text{ m of air column}$$

##### 5.4.2 Loss of head due to viscous friction for pipe length without nozzles, H2

$$l_1 = 2 + 3 + 2.14 + 3 + 1 = 11.14 \text{ m} \quad (11)$$

$$H2 = \frac{f_1 V^2}{2gD} (\text{Kothandaraman C P et al 2012}) \quad (12)$$

$$A_{pipe} \times V = q_T$$

$$V = q_T / A_{pipe}$$

$$A_{pipe} = \pi \times (0.02)^2 / 4$$

$$= 3.1416 \times 10^{-4} \text{ m}^2 \quad (13)$$

From equations (4) and (12)

$$V = 6.7802 \times 10^{-3} / (3.1416 \times 10^{-4})$$

$$= 21.582 \text{ m/s} \quad (14)$$

$$f = 0.184 / Re_D^{0.2} (\text{Kothandaraman C P et al 2010})$$

$$= 0.184 / 25465^{0.2}$$

$$= 0.02418 \quad (15)$$

From equations (11), (12), (14) & (15)

$$H2 = 319.7392 \text{ m of air column}$$

##### 5.4.3 Loss of head due to viscous friction for pipe length with nozzles, H3

This is similar to loss of head in a pipe with varying discharge.

Width of One panel,  $W = 1.27 \text{ m}$

For 9 panels,  $l_2 = 9 \times 1.27 = 11.43 \text{ m} \quad (16)$

$$H3 = \frac{64 f q_T^2 l_2}{6 g \pi^2 D^5} \quad (17)$$

(Domkundwar V M et al 2006)

From equations, (4), (15), (16) & (17)

$$H3 = 437.4188 \text{ m of air column}$$

##### 5.4.4 Loss of head due to bends in pipe, H4

$$H4 = \text{No. of bends} \times K_b \times V^2 / (2 \times g)$$

No of bends = 4,  $K_b = 0.5$

$$H4 = 4 \times 0.5 \times V^2 / (2 \times g) \quad (18)$$

From equations (14) & (18)

$$H4 = 47.4804 \text{ m of air column}$$

##### 5.4.5 Head required for cause the velocity head, H5

$$H5 = V^2 / (2 \times g) \quad (19)$$

From equations (14) & (19)

$$H5 = 23.7402 \text{ m of air column}$$

##### 5.4.6 Loss of head at entry, H6

$$H6 = K_e \times V^2 / (2 \times g) \quad (20)$$

$$K_e = 0.5$$

From equations (14) & (20)

$$H6 = 11.8701 \text{ m of air column}$$

##### 5.4.7 Loss of head due to fittings, H7

$$H7 = \text{No. of fittings} \times K_f \times V^2 / (2 \times g)$$

No of fittings = 5,  $K_f = 0.5$

$$H7 = 5 \times 0.5 \times V^2 / (2 \times g) \quad (21)$$

From equations (14) & (18)

$$H7 = 59.3505 \text{ m of air column}$$

#### 5.5 Optimisation of diameter for minimum head losses and calculation of power of blower

Total head loss,

$$H = H1 + H2 + H3 + H4 + H5 + H6 + H7$$

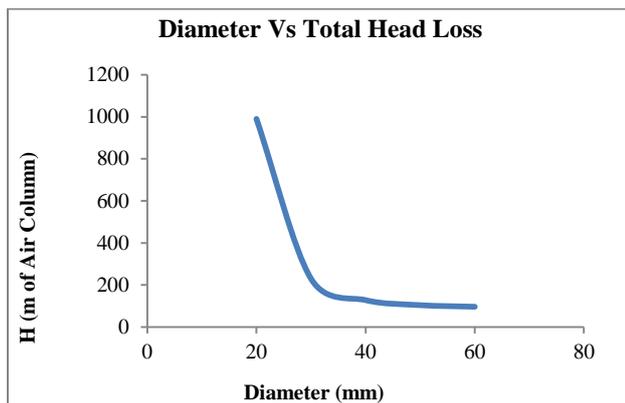
$$= 989.9962 \text{ m of air column} \quad (22)$$

Now we calculate the parameters taking pipe diameters as 30, 40, 50, 60 mm as done above for pipe diameter 20 mm and the results are tabulated in Table 2.

**Table 2 :** Parameters at different Pipe diameters

Dia	Reynolds No	Nusselt No	Lpipe	H
mm			m	m of air column
20	25465	69.155	2.139	989.996
30	16976	49.998	2.959	230.066
40	12732	39.719	3.725	128.123
50	10186	33.225	4.453	104.176
60	8488	28.716	5.152	96.482

The variation of Total Head Loss with Diameter is shown in Fig 6. Total Head loss is too high at D = 20 mm. Further, we find that at D = 50 mm we are close to asymptote. Hence the optimum diameter for this system is D = 50 mm. Therefore  $L_{pipe} = 4.45$  m



**Fig 6 :** Variation of Total head Loss vs. Diameter

Pumping power required can now be calculated.

$$P = \dot{m}_T g H$$

From equations (5) and Table 2

$$P = 7.6481 \times 10^{-3} \times 9.81 \times 104.176 = 7.816 \text{ W}$$

Assuming overall efficiency of blower

$$\eta_o = 50\%$$

Power of blower required,

$$P_{Blower} = P / \eta_o = 7.816 / 0.5 = 15.632 \text{ W}$$

**Conclusions**

Eureka, a viable Panel Cooling System is proposed consuming rather low pumping power. This is achieved by introducing the innovative concept of *Central cooling*. Hence it is logical to call it *Central Panel Cooling System (CPCS)*. It helps to increase the *Effectiveness* (section 3.4) and reduce the *Capital cost per unit power output*.(section 3.5)

Moreover, by coupling this system with Ground-coupled heat exchanger to reduce the temperature of *working fluid* gives it the name *Ground-Coupled Central Panel Cooling System (GC-CPCS)* rightfully so.

**References**

Arora S C, Domkundwar S, Domkundwar Anand V, ( 2001-2002), A Course in heat and mass transfer, *Dhanpat Rai & Co. (P) Ltd. [ISBN 81-7700-029-2]*

Bhatia A, Centralized Vs Decentralized Air Conditioning Systems, *Course No :M05-012, Continuing Education and Development, Inc., NY, info@cedengineering.com*

Carlson David E., Wronski Christopher R., (2005), Amorphous Silicon Solar Cells, *Solar Cells Materials, Manufacture and Operation, Elsevier*

Cruey Bryce, King Jordan, Tingleff, (2006), Cooling of photovoltaic Cells, <http://bob.tingleff.com/pvcooling.pdf>

Domkundwar V M, Domkundwar Anand V,(2006), Fluid Mechanics and Hydraulic Machines, *Dhanpat Rai & Co. (P) Lt*

Garde R J, (2012), Fluid Mechanics, *New Age International (P)Limited, Publishers, New Delhi. ISBN 978-81-224-3016-5*

Garg H P, Prakash J,(1997), Solar Energy Fundamentals and Applications , *Tata McGraw- Hill Publishing Company Limited, New Delhi*

Ground-Coupled Heat Exchanger, [http://en.wikipedia.org/wiki/Ground-coupled\\_heat\\_exchanger](http://en.wikipedia.org/wiki/Ground-coupled_heat_exchanger)

Irena Working Paper,(2012), International Renewable Energy Agency, *Renewable EnergyTechnologies : Cost Analysis Series Volume 1 Power Sector Issue 4/5, Solar Photovoltaics,*

Katkar A A, Shinde N N, Patil P S, (2011) Performance & Evaluation of Industrial Solar Cell w.r.t Temperature and Humidity”, *International Journal of Research in Mechanical Engineering & Technology Vol1, Issue 1, ISSN : 2249-5762 (Online)*

Khan B H (2004), Non-Conventional Energy Resources, *Tata McGraw-Hill Publishing Company Limited, New Delh*

Kothandaraman C P, Subramanyan S, (2010), Heat and Mass Transfer Data Book, *New Age International(P) Ltd., Publishers, ISBN 978-81-224-3123-*

Kothandaraman C P, Rudramoorthy,(2012), Fluid Mechanics and Machinery, *New Age International(P) Ltd., Publishers, ISBN 978-81-224-3398-*

Osterwald Carl R.,(2005), Standards Calibration and Testing of PV Modules and Solar Cells, *Solar Cells Materials, Manufacture and Operation, Elsevier*

Royne Anja, (2005), Cooling devices for densely packed High Concentration PV arrays, *A Thesis submitted to the University of Sydney for the degree of Master of Science*

Sahay Amit, Sethi V K, Tiwari A C(2013) , A comparative study of attributes of Thin Film and crystalline Photovoltaic cells, *VSRD International Journal of Mechanical, Civil, Automobile & Production Engineering, Vol 3, Issue 7 July 2013; www.vsrjournals.com*

Sukhatme S P (1984), Solar Energy- Principles of Thermal Collection and Storage, *Tata McGraw-Hill Publishing Company Limited, New Delhi*

Tonui J K, Tripanagnostopoulos,(2006), Improved PV/T solar collectors with heat extraction by forced or natural air circulation, *Renewable Energy 32 (2007) 623-637, www.sciencedirect.com*

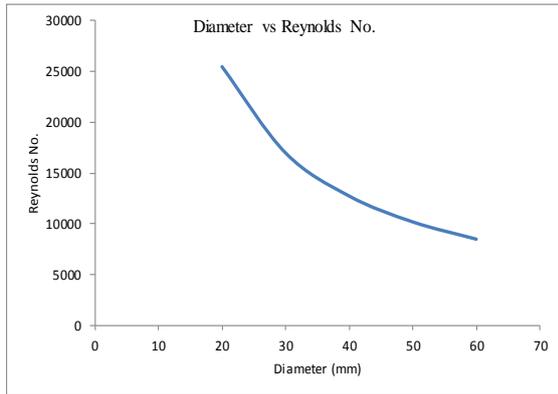
The Energy and Resiurces Institute,TERI, (2008), From Sunlight to Electricity-A practical handbook on solar photovoltaic applications”, *TERI Press, ISBN 978-81-7993-156-1, New Delh*

Yahya S M, (2002), Turbines Compressor and Fans, *Tata McGraw-Hill Publishing Company Limited, New Delhi*

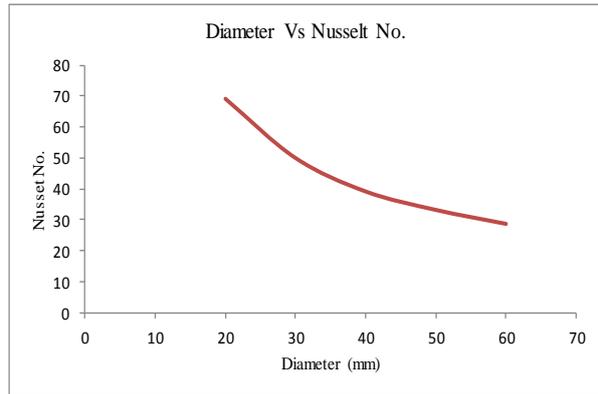
Yong Sin”Shon”Kim,(2011), Lowering the LCOE of Photovoltaic Systems, *2011 UC Solar Research Symposium, Dec 09, 2011, http://ucsolar.org*

**Appendix**

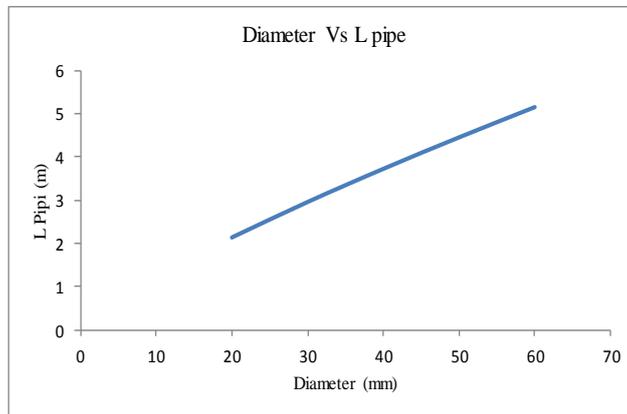
The variation of Reynolds No., Nusselt No. and Length of underground pipe is given for academic interest only.



**Fig 6 :** Variation of Reynolds No. vs. Diameter



**Fig 7 :** Variation of Nusselts No. vs. Diameter



**Fig 7 :** Variation of Length of pipe vs. Diameter