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Research Article

Thermodynamic investigation of solar energy conversion into work

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Abstract

Using a simple thermodynamic upper bound efficiency model for the conversion of solar energy into work, the best material for a converter was obtained. Modifying the existing detailed terrestrial application model of direct solar radiation to include an atmospheric transmission coefficient with cloud factors and a maximum concentration ratio, the best shape for a solar concentrator was derived. Using a Carnot engine in detailed space application model, the best shape for the mirror of a concentrator was obtained. A new conversion model was introduced for a solar chimney power plant to obtain the efficiency of the power plant and power output.

1. INTRODUCTION

A system that collects and converts solar energy in to mechanical or electrical power is important from various aspects. There are two major types of solar power systems at present, one using photovoltaic cells for direct conversion of solar radiation energy in to electrical energy in combination with electrochemical storage and the other based on thermodynamic cycles. The efficiency of a solar thermal power plant is significantly higher [1] compared to the maximum efficiency of twenty percent of a solar cell. Although the initial cost of a solar thermal power plant is very high, the running cost is lower compared to the other power plants. Therefore most countries tend to build solar thermal power plants. Big villages in countries like Switzerland and Spain totally depends on the solar thermal electricity. Solar thermal power plants with parabolic trough concentrators are very much suitable for arid country like Sri Lanka. An advantage of

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using a large scale solar thermal power plant over other power plants is the reduction in emissions of CO_2 and other gases.

The main aim of any energy conversion model is to establish an upper limit for the conversion efficiency of solar energy into work. In a thermodynamic model, a solar concentrator reflects (reflector) the flux of solar radiation toward a collector (absorber) where a working fluid is heated up to drive a convectional engine [2].

A very general thermodynamic model can be used in obtaining upper bound efficiency of a solar energy power plant as proposed by Jeter [3], by Spanner [4] or by Landsberg-Petela-Press [5,6]. Badescu [7] recently proposed a thermodynamic treatment to obtain the last efficiency and subsequently generalized to the dilute radiation to be of practical interest. Using Badescu's model, efficiencies for various materials of the converter (absorber) was calculated in order to find the best material.

More detailed models take into account the nature of incoming radiation and different design parameters of the conversion system. In detailed thermodynamic models more realistic upper bounds are obtained. Since the increase in the model's complexity is accompanied by tedious calculations, models with easy computation of efficiency were used. Detailed models are classified into two categories, terrestrial and space applications. A model for terrestrial application has to take into account the direct and diffuse components of the solar radiation at the ground level. Since the direct radiation can be concentrated, the power plants designed to use direct solar radiation have a higher efficiency than a hypothetical device converting only diffuse components. The existing terrestrial application model for direct solar radiation was modified to include an atmospheric transmission coefficient that takes into account the cloud factors. Using this modified model, the optimum temperature and the maximum efficiency were studied relative to the concentration ratio for a sunny day. Since these calculations showed that the maximum efficiency of a solar thermal power plant strongly depends on concentration ratio, shape of a solar concentrator is a key factor in designing solar energy conversion models. Consequently, the efficiencies for solar concentrators in the shapes of cylindrical parabolic trough and flat plate collector were calculated for a sunny day. The model was finally modified to include a maximum concentration ratio and thereby the optimum temperature and efficiency were calculated for a sunny day.

A space power station uses beamed solar radiation only and differs from a terrestrial plant due to the fact that the heat is rejected from the thermal engine through radiation in space and by convection on earth. In space application model, the efficiency was obtained in terms of a parameter which depends on the optical reflectance of the mirror of the concentrator, the emittance, absorbance, temperature of the collector and geometrical concentration ratio. The maximum efficiency and the optimum optimorum value of this parameter were calculated relative to geometrical concentration ratio and mirror factor (the ratio of surface area of the mirror to the concentrator opening area). Since these calculated values showed that the efficiency of a space solar thermal power plant increases with the shape factor of the mirror, shape factors for different types of the concentrators were calculated to obtain the best shape for the mirror.

A solar chimney power plant converts global irradiance into electricity. It uses an array of flat, movable mirrors to focus the sun's rays upon a collector tower. The sun heats up the ground and the air underneath the collector roof. The heated air follow the upward incline of the roof until it reaches the chimney and flows at high speed through the chimney driving wind generators at its bottom. The ground under the collector roof behaves as storage medium and heat up the air for a significant time after sunset. Since the efficiency of a solar chimney power plant is below two percent depending mainly on the height of the tower [8], these power plants can only be constructed on land which is very cheap or free. Chimney power plant has a major advantage over wind farms and solar generators. It can operate without wind and solar cells stores heat during the day allowing it to produce electricity continuously [9]. A thermodynamic theoretical model for solar chimney plant was introduced to obtain the efficiency and output.

2. THERMODYNAMIC MODEL FOR UPPER BOUND EFFECIENCY

A very general thermodynamic model can be used in obtaining upper bound efficiency of a solar energy power plant converting solar radiation into work by taking into account the two energy sources, the Sun and the ambient and the optical properties of the absorber for black body radiation by using the thermodynamic treatment of Badescu [7] . This model gives the following formula for the efficiency (η) of a solar absorber or converter for direct and diluted solar radiation in terms of absorbance (a) and emittance (e) of the material, geometrical view factor (A), diluted factor for radiation (ε), Sun's temperature (T_s) and ambient temperature (T_o),

$$\eta = a\left\{1-\frac{4}{3}\frac{1}{\left(\left(a/eA\right)\varepsilon\right)^{1/4}}\frac{T_0}{T_s}+\frac{1}{3}\left[\frac{1}{\left(\left(a/eA\right)\varepsilon\right)^{1/4}}\frac{T_0}{T_s}\right]^4\right\} \tag{1}$$

where the geometrical view factor for the solid angle Ω_s subtended by the Sun is

$$A(\Omega_s) = \frac{\Omega_s}{\pi}\left(1-\frac{\Omega_s}{4\pi}\right) = 2.17\times10^{-5} \quad \left(\Omega_s \approx 6.835\times10^{-5}\,\text{sr}\right).$$

For undiluted solar radiation ($\varepsilon = 1$) of Sun's temperature $T_s = 5762\,\text{K}$ and ambient temperature $T_o = 300\,\text{K}$, the efficiencies for different converter materials were calculated and tabulated in Table 1.

The efficiency increased with higher absorbance of the converter material irrespective of its emittance. Therefore the best efficiency can be gained by using a converter made from a material having highest absorbance, in this case zinc or aluminum paint. In order to obtain a significant increment in efficiency, the emittance had to be decreased by an order of 10^{-5}. Therefore the value of emittance of the converter was fixed for the calculations.

Table 1: Efficiencies of different solar converter materials

Material	Absorbance (a)	Emittance (e)	Efficiency	Range of a for efficiency within $\pm 5\%$
silver	0.07	0.02	7%	0.02-0.12
platinum	0.10	0.05	10%	0.05-0.15
copper	0.25	0.15	25%	0.20-0.25
zinc	0.55	0.05	55%	0.50-0.60
Aluminum paint	0.55	0.55	55%	0.50-0.60
Aluminum polished	0.15	0.08	15%	0.10-0.20

3. THERMODYNAMIC MODEL FOR TERRESTRIAL APPLICATION

In detailed terrestrial power plant models, the radiation at the ground level is composed of direct and diluted components. By considering a black body converter which utilizes the flux radiation that is effected by transmission through the atmosphere, a formula for the efficiency [7] of direct solar radiation can be obtained by

$$\eta = \left(1-\frac{T_0}{T}\right)\left(1-\alpha\frac{T^4-T_0^4}{T_s^4}\right) \quad \text{and} \quad \alpha = \frac{2}{C\tau\left(1-\cos 2\delta\right)} . \qquad (2)$$

The parameter α depends on the concentration ratio (C), atmospheric transmission coefficient (τ) and half-angle (δ) of the cone subtended by the solar disk. The optimum converter temperature (T_{opt}) can be found by maximizing the efficiency with respect to temperature, i.e.

$$\left(\frac{\partial\eta}{\partial T}\right)_{T=T_{opt}} = 4T_{opt}^{\ 5} - 3T_0T_{opt}^{\ 4} - \frac{1}{\alpha}T_0T_s^{\ 4} = 0 . \qquad (3)$$

The main advantage of using only direct solar energy is that it can be concentrated. Diffuse solar radiation is considered as diluted blackbody radiation and the efficiency of the converter is given by [7]

$$\eta_{diff} = \left(1-\frac{T_0}{T}\right)\left(1-\frac{e\pi}{aC\Omega_s}\frac{T^4}{T_s^4}\right).$$

The optimum converter temperature T_{opt} obtained by maximizing the efficiency is

$$\left(\frac{\partial\eta}{\partial T}\right)_{T=T_{opt}} = 4T_{opt}^{5} - 3T_0 T_{opt}^{4} - \frac{aC\Omega_s}{e\pi} T_0 T_s^{4} = 0 .$$

A key factor in determining the efficiency of terrestrial model for direct solar energy is the atmospheric transmission coefficient (τ). The atmospheric transmission coefficient (τ) was modified to take into account cloud factors for high, middle and low regions of atmosphere σ_H , σ_M and σ_L respectively [6].

$$\tau = (0.6 + 0.2\sin\psi)(1 - 0.4\sigma_H)(1 - 0.7\sigma_M)(1 - 0.4\sigma_L) \qquad (4)$$

where ψ is the angle between the normal to earth surface and the incident solar ray. The atmospheric transmission coefficient which varies between 0 and 1 can be calculated from the above expression in any place of earth. In general for a sunny day with radiation falling normally on the clouds, the cloud factors have values $\sigma_H = 0.5, \sigma_M = 0.5$ and $\sigma_L = 0.5$. Consequently the transmission coefficient for a sunny day is $\tau = 0.3328$.

The optimum temperature and maximum efficiency with respect to concentration ratio were obtained for a sunny day from the following expressions

$$\eta_{max} = \left(1 - \frac{T_0}{T_{opt}}\right)\left(1 - \alpha\frac{T_{opt}^{4} - T_0^{4}}{T_s^{4}}\right) \qquad \alpha = \frac{2}{0.3328(1 - \cos 2\delta)C} \qquad (5)$$

where $\delta = 0.265^\circ$ is the half angle of the cone subtended by the Sun (this value is an average for a power plant). A graph of maximum efficiency and optimum temperature with respect to concentration ratio were calculated for direct sunlight using equation 3 and 5 and plotted in Fig. 1. Since the optimum temperature has to be less than the source temperature and greater than the ambient temperature, the best value obtained for optimum temperature was $T_{opt} = 2152.1\,K$ and the corresponding maximum efficiency was $(81.30 \pm 0.04)\%$.

Calculations showed that the maximum efficiency of a solar thermal power plant strongly depends on the concentration ratio, decreasing abruptly with the decrease in concentration ratio. Therefore the shape of the solar concentrator is a key factor in designing a solar energy conversion model. A cylindrical parabolic trough is one of the best known commercially available solar concentrator. Geometrically, the parabola has a unique reflector shape that can focus the solar radiation into a single point parallel to its optical axis. In the modified model, the optimum concentration ratio for a cylindrical trough concentrator is introduced as [10],

$$C_{cyl} = 1/\pi\sin\delta \ . \qquad (6)$$

The concentration ratio calculated from the above formula was 4.44. For a cylindrical trough concentrator on a sunny day, the optimum temperature and the maximum efficiency calculated were 1842.1 K and $(79.80 \pm 0.04)\%$ respectively.

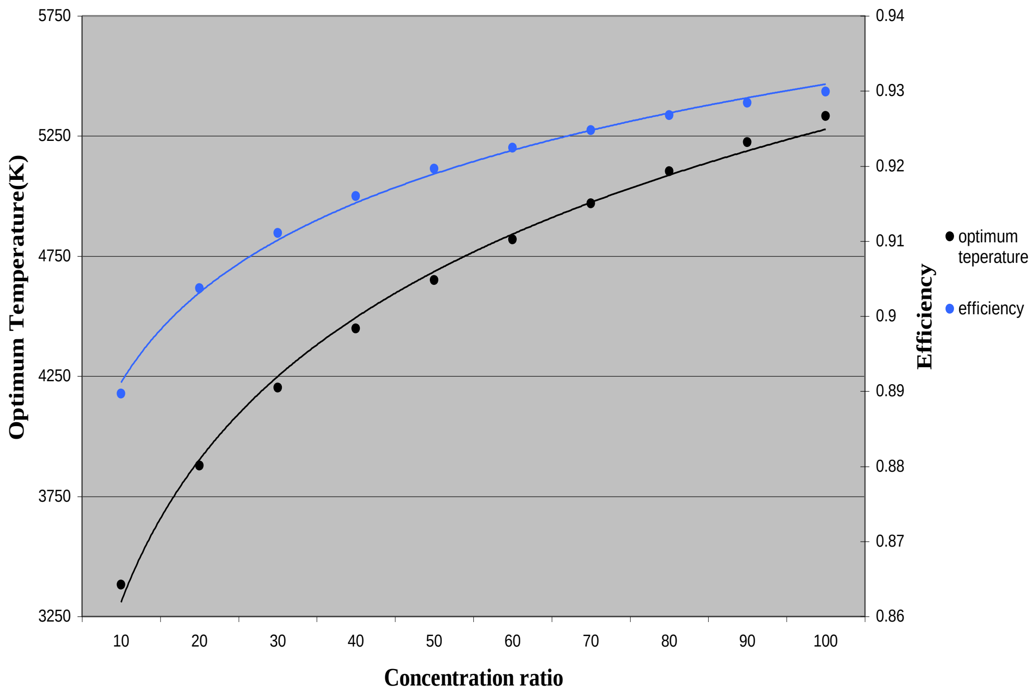

Fig. 1 The graph of maximum efficiency & optimum temperature as functions of concentration ratio for a sunny day.

Another type of concentrator commonly used is a flat plate collector. For a flat plate collector, the concentration ratio is introduced as [6]

$$C_{flat} = \frac{1}{l \sin \delta} - \frac{3}{2}. \qquad (7)$$

The efficiency of a flat plate collector depends on the length of the collector. On a sunny day, for flat plate collectors of lengths $l = 0.5\,m$ and $l = 0.75\,m$, the maximum efficiencies calculated were η = $(83.6 \pm 0.05)\%$ and η = $(79.2 \pm 0.05)\%$ respectively.

Since in direct and diffuse radiation models, the concentration ratio play an important role in determining the efficiency, the key factors governing the concentration ratio have been studied in great detail. Concentration ratio (C) [1-7] of a solar concentrator is defined as the ratio of collecting aperture area A_a to the absorber area A_{abs} $(i.e.\ C = A_a / A_{abs})$. A solar concentrator is used to increase the flux density of solar radiation on the solar absorber. By assuming the radiation to be uniformly distributed over the incident angles $|\theta| < |\theta_{\max}|$ of the aperture area, a highest possible value for concentration ratio can be calculated. A three dimensional view from the sun (radius *r*) of a solar converter system with a concentrator aperture placed at a distance *R* from it with aperture area A_a and absorber area A_{abs} is shown in Fig. 2.

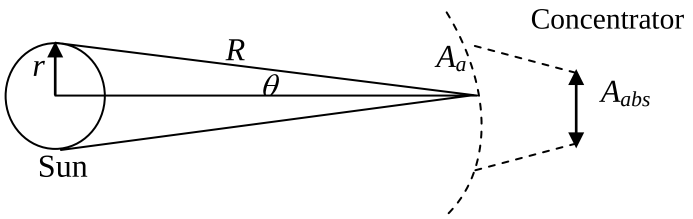

Fig. 2 Sun at a distance *R* from a concentrator with aperture area A_a and absorber area A_{abs}

The fraction of the incident heat from the Sun intercepted by a perfect concentrator aperture area A_a is $Q_{s,abs}$

$$Q_{s,abs} = A_a \frac{r^2}{R^2} \sigma T_s^{\,4} . \qquad (8)$$

A perfect absorber (blackbody) at temperature T_{abs} radiates energy $A_{abs}\sigma T_{abs}^{\,4}$. Only a fraction $Q_{abs,s}$ of this radiation reaches the concentrator i.e.

$$Q_{abs,s} = A_{abs}\sigma T_{abs}^{\,4} E_{abs,s} \qquad (9)$$

where $E_{abs,s}$ called the exchange factor is the fraction of heat absorbed by the system with respect to heat of the Sun. Therefore exchange factor cannot exceed unity. According to second law of thermodynamics when the source and absorber are at the same temperature no net heat is transferred between these bodies. Therefore

$$Q_{s,abs} = Q_{abs,s} \quad \text{if} \quad T_{abs} = T_s . \qquad (10)$$

Equations 8 and 9 lead to:

$$\frac{A_a}{A_{abs}} = \frac{R^2}{r^2} E_{abs,s} . \qquad (11)$$

Using the geometry on Fig 2, the above expression reduces to

$$C_{ideal} = \frac{A_a}{A_{abs}} = \frac{E_{abs,s}}{\sin^2 \delta} . \qquad (12)$$

where δ is the minimum possible value for $\theta_{\max}$. As the maximum possible value of $E_{abs,s}$ is unity, the concentration ratio must satisfy the condition [1],

$$C_{ideal} \le 1/\sin^2 \delta . \qquad (13)$$

The concentration ratio can be increased by a factor of n^2 by covering the parallel slabs with transport medium having index of refraction n i.e.,

$$C_{ideal} \leq n^2 / \sin^2 \delta . \qquad (14)$$

These equations imply that the maximum concentration value is independent of the size or the shape of the concentrator. By taking in to account that the angular diameter of sun is 32 minutes of an arc ($\delta = 16'$), a maximum possible concentration of 46000 was obtained for $n = 1$.

A modified model for direct solar radiation is introduced by taking in to consideration the maximum concentration ration and cloud factors. The efficiency of this model is given by

$$\eta = \left(1 - \frac{T_0}{T}\right)\left(1 - \alpha' \frac{T^4 - T_0^{\ 4}}{T_s^{\ 4}}\right) \qquad (15)$$

where $$\alpha' = \frac{2\sin^2 \delta}{(1-\cos 2\delta)(0.6 + 0.2\sin\psi) A(\Omega_s)(1-0.4\sigma_H)(1-0.7\sigma_M)(1-0.4\sigma_L)} . \qquad (16)$$

The optimum converter temperature is obtained from maximizing the efficiency

$$\left(\frac{\partial \eta}{\partial T}\right)_{T=T_{opt}} = 4T_{opt}^{\ 5} - 3T_0 T_{opt}^{\ 4} - \frac{1}{\alpha'} T_0 T_s^{\ 4} = 0 .$$

The maximum efficiency of the modified model is given by

$$\eta_{max} = \left(1 - \frac{T_0}{T_{opt}}\right)\left(1 - \alpha' \frac{T_{opt}^{\ 4} - T_0^{\ 4}}{T_s^{\ 4}}\right) .$$

In the modified model, the radiation is assumed to be black-body radiation so that the geometrical view factor $A(\Omega_s)$ can be taken as unity. For a sunny day, the optimum temperature and parameter α' were calculated for maximum possible concentration $C = 46000$. These were T_{opt} = 2152.1 K and α' = 3.0 respectively. Consequently, the maximum efficiency obtained from the modified model was $(81.30 \pm 0.04)\%$.

4. SPACE APPLICATION MODEL

In a detailed solar space thermal power plant, the main components of the plant are solar concentrator, collector (receiver), thermal engine and heat radiator [7] (Fig. 3). The solar concentrator has an opening area A_o and a mirror with optical reflectance ρ_m, surface area A_m and a superficial mass density d_m. The collector has area A_c and its temperature, emittance and absorbance all consider being uniform, are denoted by T_c, e_c and

a_c respectively. The radiator superficial mass density is d_r and the geometrical concentration ratio $C_n = A_o / A_c$ satisfy $C_n f A_c + s A_r = A_e$ $\left(f = A_m / A_o, s = d_r / d_m \right)$

Considering the thermal engine to be a Carnot engine, the efficiency can be obtain by,

$$\eta = a_c \rho_m \frac{x-1}{x+3} \; ; \qquad x = \frac{a_c \rho_m}{e_c} B(C_n) \left(\frac{T_s}{T_c} \right)^4 . \qquad (17)$$

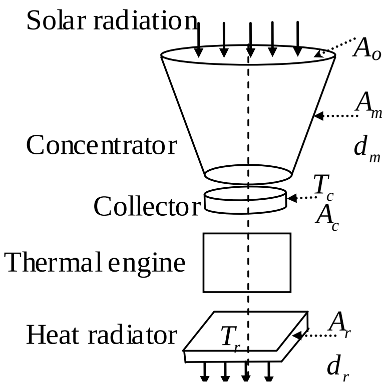

Fig. 3 The elements of a solar space power station

x_{opt} is obtained by maximizing the efficiency $d\eta / dx = 0$ i.e.,

$$\left(\frac{e_c A_c}{e_r A_r} \right) (x_{opt} - 1) \left(1 + \frac{x_{opt}}{3} \right)^3 = 1 \; , \qquad (18)$$

e_r and A_r are emittance and area of the radiator respectively. The maximum efficiency is

$$\eta_{\max} = a_c \rho_m \frac{x_{opt} - 1}{x_{opt} + 3} . \qquad (19)$$

The optimum optimorum factor $x_{opt,opt}$ indirectly relates to the optimum temperature of the power plant. In order to obtain an optimum temperature between the Sun and the ambient, the maximum emittance of collector and radiator were chosen as $e_r = 0.8, e_c = 0.9$ and reflection coefficient of the mirror as $\rho_m = 0.9$. For the total absorbance of solar radiation, the optimum optimorum value of x and the second maximum efficiency of the space power plant were calculated. These were $x_{opt,opt} = 1.52$ and $\eta_{max,max}$ = $(10.3 \pm 0.01)\%$ respectively.

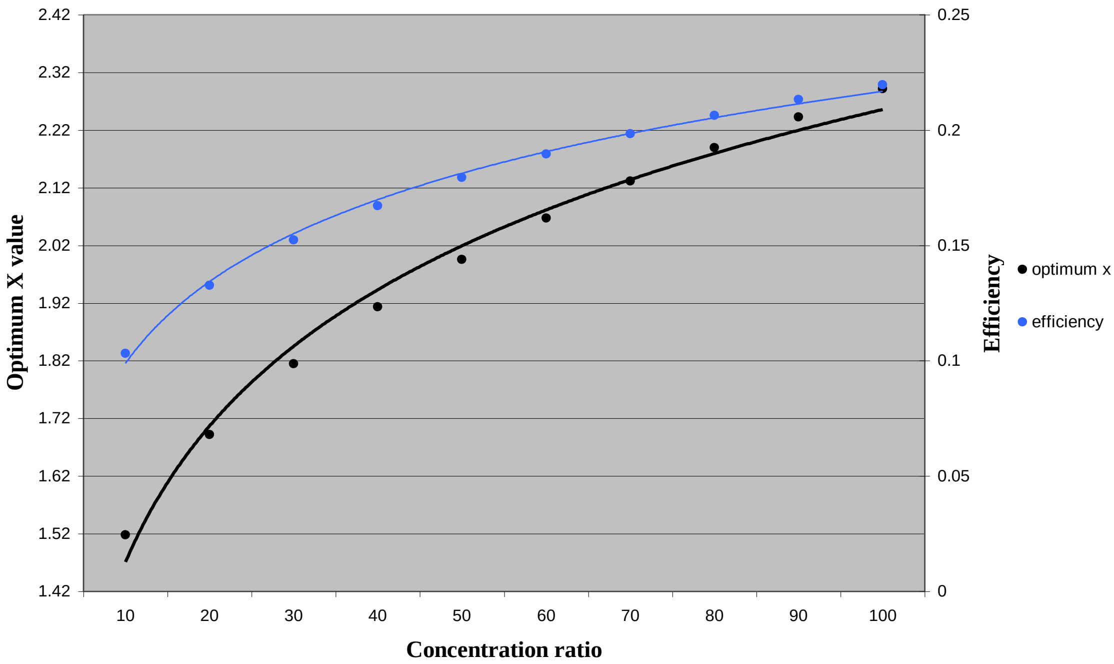

Fig. 4 The graph of second maximum efficiency $\eta_{max,max}$ and $x_{opt,opt}$ as a function of concentration ratio C_n for a classical thermodynamic model for f = 1.03 & s = 10.

The dependency of the second maximum efficiency $\eta_{max,max}$ and $x_{opt,opt}$ factor of the power plant on concentration ratio for $f = 1.03$ and $s = 10$ were calculated and plotted in Fig. 4. The calculated values showed that the efficiency of a space solar thermal power plant increased with the shape factor of the mirror. Therefore a mirror with highest shape factor will give the highest efficiency. The shape factors for different shapes of mirrors are tabulated in Table 2 and plotted in Fig. 5.

Table 2 Different type of mirror shapes as a function of $k = h/r$ (h and r are depth and entrance size of the mirror) [3]

Mirror	Shape factor $f(k)$
Conical	$(1+k^2)^{1/2}$
Sphere	$1+k^2$
Circular cylinder	$\frac{1}{2}\frac{k^2+1}{k} arc\tan\frac{2k}{1-k^2}$
Parabolic cylinder	$\frac{1}{2}(1+4k^2)^{1/2}+\frac{1}{4k}\ln\left[2k+(1+4k2)^{1/2}\right]$
Paraboloid	$\frac{2}{3}\left\{\left[(2k)^{2/3}+(1/2k)^{4/3}\right]^{3/2}-\frac{1}{4k^2}\right\}$

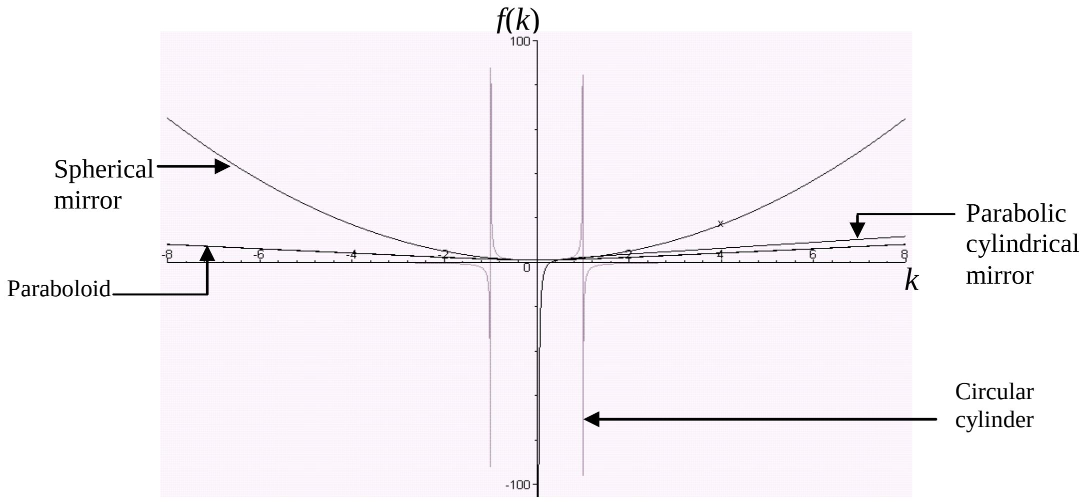

Fig. 5 Shape factors of different type of mirrors

Fig. 5 shows that the spherical mirrors have the highest shape factor and will be the best shape for the mirror. Because of the construction difficulties, in some instances, the parabolic cylindrical mirrors with the next highest shape factor are used.

5. SOLAR CHIMNEY POWER PLANT

The solar chimney power plant basically operates like a hydroelectric power plant, but instead of water it uses hot air. A round ascending glass roof with a diameter of several thousand meters is used as a collector. A chimney in the middle sucks the ascending heated air and the air ascends with a velocity about fifteen meters per second. The arising air suction drives the wind turbines which are placed in the chimney. The turbines are used together with a generator and a gearing to produce current [12]. A solar chimney power plant is shown in Fig. 6.

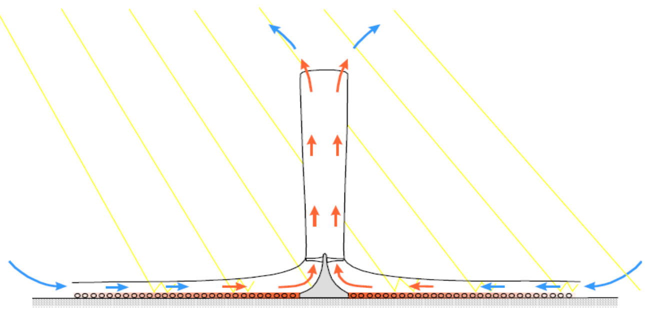

Fig. 6 Working principle of the solar chimney: glass roof collector, chimney tube and wind turbines

A thermodynamic model is introduced to obtain the efficiency of a solar chimney power plant in terms of the efficiencies of the turbine and the tower. The overall efficiency of the power plant is introduced as,

$$\eta = \eta_{turbine}.\eta_{tower} \qquad (20)$$

where $\eta_{turbine}$ and η_{tower} are the individual efficiencies of turbine and solar tower respectively. Efficiency of tower can be give [13],

$$\eta_{tower} = \frac{P_{tot}}{\dot{Q}} \qquad (21)$$

where P_{tot} and $\dot{Q}$ are the power output from the tower and solar input to the tower respectively. Output power is given by,

$$P_{tot} = \frac{1}{2} m\dot{v}^2_{tower,\max} \qquad (22)$$

where $v_{tower,\max}$ is the maximum speed of the air inside the tower.

From Boussinesq approximation [14], the speed reached by free convection currents can be expressed for a tower of height *H* as,

$$v_{tower,\max} = \sqrt{2.gH_{tower}.\frac{\Delta T}{T_0}} \qquad (23)$$

where ΔT is the temperature rise between ambient and the collector. Then tower efficiency is given by [10, 11] ,

$$\eta_{tower} = \frac{g.H}{C_p.T_0} \qquad (24)$$

where C_p and g are the specific heat capacity of air at constant pressure and gravitational acceleration respectively. T_0 is the ambient temperature. This simplified expression explains one of the basic characteristics of the solar tower. According to our model, the efficiency fundamentally depends only on its height. Calculations using Boussinesq approximation [14] showed that for tower heights less than 1000 *m*, the deviation from exact solution was negligible. With the knowledge of the efficiency of the turbine, the efficiency of solar chimney power plant can be obtained. In general, the efficiency of a turbine is 70% and the heat capacity of air is $C_p = 1010\ J/kgKs$. For a solar tower of 500 *m* height, the efficiency calculated was $\eta = (1.600 \pm 0.001)\%$.

The power output of this model is introduced as,

$$P = G_{sc}.A_{coll}.\eta_{tower}.\eta_{turbine} \qquad (25)$$

where G_{sc} is the solar constant ($G_{sc} = 1367\ \mathrm{W\,m^{-2}}$) and A_{col} is the area of the collector. The power output calculated for a collector of radius $1000\,m$ is $P = (48.0 \pm 0.1)\,\mathrm{MW}$. This theoretical value is higher than the practical value of 35 MW [14]. In this theoretical model, the collector was assumed to absorb solar radiation of all wavelengths. The difference in the calculated and practical values of the power is due to the failure of the collector to absorb the whole solar spectrum.

6. CONCLUSIONS

The models described were built under the assumption that solar radiation is a photon system and undiluted $(\varepsilon = 1)$. The calculations of the upper bound efficiency model showed that the absorbance coefficient of the converter has to be increased to obtain a higher efficiency. Zinc and Aluminum paint gave the maximum value for the efficiency. The variation of efficiency with emittance coefficient was very small. Therefore its value was fixed for the calculations. The modified detailed terrestrial application model for direct solar radiation including an atmospheric transmission coefficient with cloud factors showed that the maximum efficiency of a solar thermal power plant strongly depends on the concentration ratio. Thereby the shape of the solar concentrator is a key factor in designing solar energy conversion models. The efficiency of a flat plate collector with smaller length ($l \simeq 0.5m$) was greater than a cylindrical parabolic trough. The modified model with a maximum concentration ratio on a sunny day gave an optimum temperature of $T_{opt} = 2152\,K$ and a 81% maximum efficiency. Detailed space application model was studied for different types and shapes of the concentrators namely, parabolic troughs, parabolic dishes and central receivers. The best efficiency was obtained by using a concentrator with a spherical mirror. Parabolic troughs and parabolic dishes also gave good efficiency. A parabolic dish has a limitation to its maximum size. Since parabolic troughs can be arranged over a large space of ground, they have no limitations for a maximum size. In general, efficiency of solar chimney power plant is about 2%. The 98% drop is due to the temperature loss inside the tower with the altitude $\left(10^{o}C \ \ for \ \ 1000m\right)$. The calculated power output from the introduced model for a solar chimney power plant was nearly 50 MW. But in real case it is 35 MW [14]. The difference is due to the failure of the collector in absorbing the whole solar spectrum.

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