Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Fuel 85 (2006) 2561–2566

FUEL

www.fuelfirst.com

The potential of solar chimney for application in rural areas of developing countries

Frederick N. Onyango, Reccab M. Ochieng *

Department of Physics, Maseno University, P.O. Box 333, Maseno, Kenya

Received 7 October 2005; received in revised form 26 April 2006; accepted 27 April 2006
Available online 5 June 2006

Abstract

Solar chimney electric power generation is one of the concepts in renewable energy technology (RET) application. The power station is based simply on the principle that warm air rises. Air underneath a glass ceiling is heated by solar radiation and rises through a chimney. The warm air which has just risen is replaced by air from the edge of the glass ceiling which flows inward, and will then itself begin to heat up. In this way the Sun's heat radiation is converted into kinetic energy of constantly rising air to drive turbine built into the chimney. The turbine then converts the wind power by means of a generator into electrical energy. We have considered the appropriateness of a solar chimney to rural villages and highlight some features of such a power generating plant. The calculations carried out show that the power that can be generated by a solar chimney of specific dimension exhibit a minimum threshold value of $\tau = 2.9$, the temperature ratio of the difference between the collector surface temperature and the temperature at the turbine (T_s–T_H) to the difference between the air mass temperature under the roof and the collector surface temperature (T_m–T_s). Our calculations show that for $\tau = 2.9$, an appreciable electric power ($\geqslant 10^3$ W) can be generated by a sturdy and physically viable solar chimney whose dimension has been determined to be $L = 150$ m, $H = R = 1.5$ m. This the minimum dimension of a practical solar chimney electric power station would serve approximately fifty (50) households in a typical rural setting.

Keywords: Renewable energy; Solar chimney; Electric power

1. Introduction

All forms of renewable energy such as biomass, wind, photovoltaic or solar thermal are directly or indirectly linked to energy from the sun (solar energy) Fig. 1.

Solar energy is a free and a potentially viable national resource in Africa which, if harnessed appropriately could be a vital factor in improving the quality of life especially in the poor rural communities. In most cases, the technology required to exploit these resources may not require expensive high-technological installations or highly skilled manpower to operate the installations. The technology is therefore attractive for use in most of the African countries. Indeed, the possibility of creating small-scale, decentralized energy installations, which are maintained and run by local people, constitutes the most important aspect of renewable energy technology (RET); and ideally ought to form a major component in the policy making of the African Governments. Refs. [1–23] provide useful background information on solar energy and its application.

By and large RET can revitalize rural communities by creating local industries and businesses where they are implemented and most RET are environmentally friendly because they produce minimum of waste products [24]. RET can reduce mass migration of population from rural to urban areas in search of jobs in factories which can be built with the presence of some RET. It is possible to reduce the nation's bill for imported primary energy resource by using some forms of RET which may also be used as a good strategy against deforestation.

---

* Corresponding author. Tel.: +254734234938.
E-mail address: reccabo@yahoo.com (R.M. Ochieng).

0016-2361/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2006.04.029

Nomenclature

W	heat exchanged [J]	P_i	instantaneous power [W]
T	temperature [K]	L	length [m]
h	heat exchange coefficient or heat transfer coefficient [W/m^2 K]	m	mass [kg]
		ρ	density [kg/m^3]
H	height above the collector [m]	R	radius [m]
A	collector area [m^2]	u	velocity [m/s]
k	thermal conductivity [W/m K]	C_p	specific heat at constant pressure [J/kg K]
Re	Reynolds number	α	diffusivity [m^2/s]
Pr	Prandtl number	v	kinematic viscosity [m/s]

If carefully planned and appropriately designed, renewable energy technologies can play a significant role in energy requirements for the developing countries. In this paper, we consider a typical solar chimney as one of the renewable energy technology and highlight its appropriateness to rural villages.

The ingenious yet simple design of the solar chimney electric power generating plant was conceived by Jörg Schlaich, professor at the Institute for Construction and Design (Institut für Konstruktion und Entwurf) of the University of Stuttgart. A prototype in Manzanares, south of Madrid, delivered power practically uninterrupted from the middle of 1986 until the beginning of 1989 with a peak output of 50 kW. Its collector had a diameter of 240 m while the chimney had a diameter of 10 m and was 195 m tall.

2. Solar chimney

A number of low temperature (<100 °C) solar thermal systems such as solar stills, solar dryers and water heaters have been designed and field-tested. Some of these systems which are small-scale or domestic compared to the industrial high temperature systems have been commercialized whilst others are still at the prototype stage. In Africa, high temperature (>150 °C) solar thermal systems which are suitable for industrial purposes because they can produce enough energy to run small scale industries.

A large open area with abundant sunshine can be covered with a high temperature heat absorbing selective material under a large glass roof or a suitable transparent material such as polythene. Hot air is produced by the

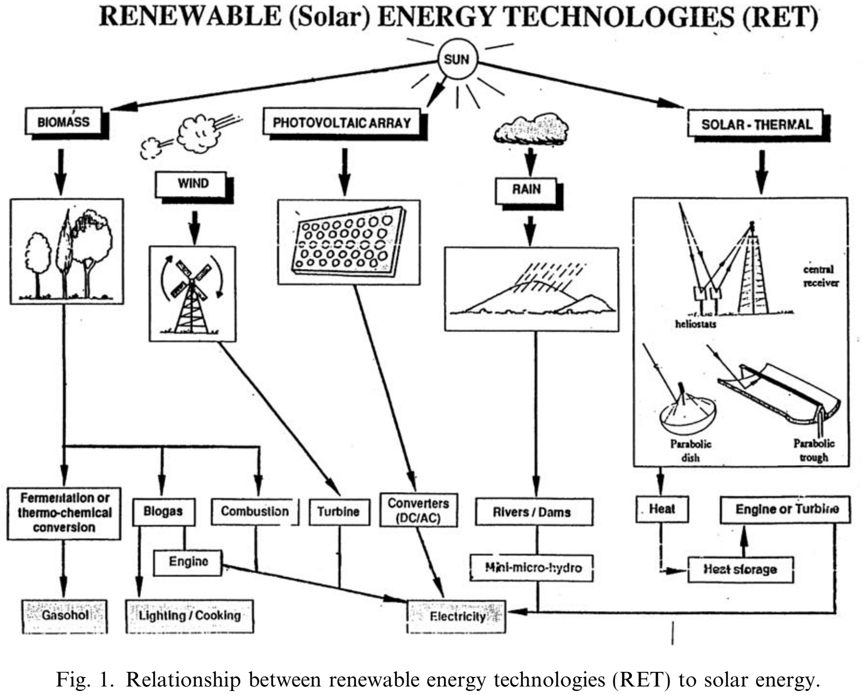

Fig. 1. Relationship between renewable energy technologies (RET) to solar energy.

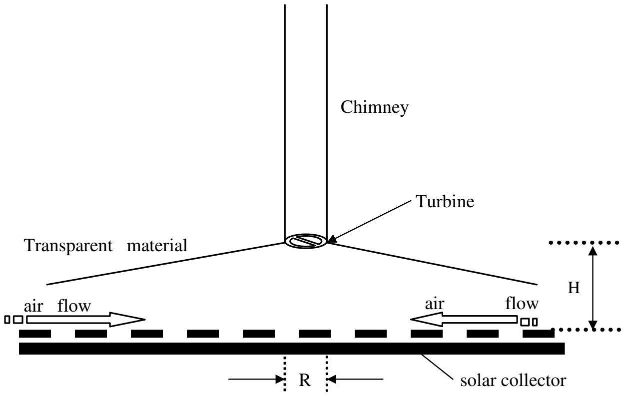

Fig. 2. Solar chimney electric power generator.

sun under the roof when the material converts solar radiation (direct and diffuse) into heat. Hot air under the roof is which is heated by the radiation flows to a chimney constructed in the middle of the roof and is drawn upwards. This upwind drives turbines installed at an appropriate height H at the base of the chimney to produce electricity. An illustration of a suitable solar chimney electric power generating plant is shown in Fig. 2.

3. Theory

The heat energy transferred from the patched surface is given by

$$W_1 = hA(T_s - T_H) \tag{1}$$

where T_s and T_H are the temperatures at the surface covered by a selective material and at any position H in the covered area A and h is the convective transfer coefficient given by

$$h = h(Re, Pr, k, L).$$

In the case of a turbine [1]

$$h = 0.036\frac{k}{L}Pr^{\frac{1}{3}}Re^{0.8} \tag{2}$$

where k is the thermal conductivity of the air, L is the width of the surface, Re and Pr are the Reynolds and Prandtl numbers, respectively [25–30].

For a square collector of sides L, the area is given by $A = L^2$ and Eq. (1) reduces to

$$W_1 = hL^2(T_s - T_H) \tag{3}$$

on the other hand heat transferred from the patched area to air under the canopy is given by

$$W_2 = \dot{m}C_p(T_m - T_s) \tag{4}$$

where T_m is the temperature of mass of air inside the chimney, and C_p is the specific heat capacity at constant pressure and m dot is the mass flow rate (kg/s) given by

$$\dot{m} = \rho_a u A_p \tag{5}$$

where ρ_a is the ambient density of the air, u is the velocity with which the mass flows.

The cross-sectional area of the opening around the square patch of side L is given by

$$A_p = 4LH$$

so that Eq. (4) can be rewritten as

$$Q_2 = 4\rho_a u C_p LH(T_m - T_s). \tag{6}$$

For a circular chimney of radius R, the velocity V at which air impinges on the rotor blades of the air turbines is given by

$$\pi R^2 V = 4LHu \tag{7a}$$

resulting in

$$u = \frac{\pi R^2 V}{4LH} \tag{7b}$$

hence the heat transfer to the air under the chimney is

$$Q_2 = \rho_a \pi R^2 V C_p(T_m - T_s). \tag{8}$$

Combining Eqs. (3) and (8), we obtain

$$h = \frac{\pi\rho_a C_p R^2 V}{L^2}\left(\frac{T_m - T_s}{T_s - T_H}\right). \tag{9}$$

Transposition of Eq. (9) gives

$$V = \frac{hL^2}{\pi\rho_a C_p R^2}\left(\frac{T_s - T_H}{T_m - T_s}\right). \tag{10}$$

Substituting known values for the constants in Eq. (10), we obtain the expression for the velocity V, at which the air impinges on the rotor blades as

$$V = \left(\frac{0.036}{\pi}\right)^5\left(\frac{\pi}{4}\right)\left(\frac{L^5k^5}{\alpha^{\frac{5}{3}}H^4\nu^{\frac{7}{3}}C_p^5\rho_a^5R^2}\right)\tau^5 \tag{11}$$

where

$$\tau = \left(\frac{T_s - T_H}{T_m - T_s}\right) \tag{12}$$

ν is the kinematic viscosity, α the thermal diffusivity of the air and k the thermal conductivity of the air at a given temperature.

If it is assumed that the area swept by the rotor is the same as the cross-sectional area of the chimney, then using Eq. (7a) the instantaneous electric power P_i produced by a single turbine is readily derived as

$$P_i = \frac{16}{27}\left(\frac{1}{2}\rho_m\pi R^2V^3\right) \tag{13}$$

where ρ_m is the density of the air at temperature T_m and the factor of $\frac{16}{27}$ is the ideal limit for the extraction of power [31,32].

From Eqs. (11) and (13), the instantaneous electric power is

$$P_i = 3.0 \times 10^{-31}\beta\left(\frac{L^{15}}{H^{12}R^4}\right)\tau^{15} \tag{14}$$

where at 300 K and one atmosphere

$$\beta = \left(\frac{\rho_{\mathrm{m}} k^{15}}{\alpha^5 C_p^{15} v^7 \rho_{\mathrm{a}}^{15}} \right) = 1.148 \times 10^{-12}. \tag{15}$$

Eq. (14) shows that the instantaneous electric power depends mainly on the dimensions of the solar chimney for a given temperature ratio, τ. Thus the equation can be treated as generic. However, except for the ambient density ρ_{a}, all other parameters in Eq. (15) vary with τ, hence β is a function of τ hereafter expressed as $\beta(\tau)$. Substituting known the constants [14,15] in Eq. (14) for dry air at one atmospheric pressure and ambient temperature ($T = 300$ K), the instantaneous power reduces to

$$P_{\mathrm{i}} = 4.48 \times 10^{-43} \times \left(\frac{L^{15}}{H^{12} R^4} \right) \tau^{15} \tag{16}$$

Using known values of ρ_{m}, k, α, C_p, v and ρ_{a} [30] one can show that $\beta(\tau)$ does not change significantly from the value obtained at 300 K and at one atmospheric pressure.

The upper and lower limits of $\beta(\tau)$ can, however, be determined through differentiation of Eq. (12).

For $T_{\mathrm{s}} > T_{\mathrm{H}}$ and $T_{\mathrm{m}} > T_{\mathrm{s}}$, Eq. (12) can be written as

$$\tau = (T_{\mathrm{s}} - T_{\mathrm{H}}) \frac{1}{T_{\mathrm{m}}} \left(1 - \frac{T_{\mathrm{s}}}{T_{\mathrm{m}}} \right)^{-1}. \tag{17}$$

Assuming that $T_{\mathrm{m}} \gg T_{\mathrm{s}}$ we can use binomial expansion on $\frac{1}{T_{\mathrm{m}}}(1 - \frac{T_{\mathrm{s}}}{T_{\mathrm{m}}})^{-1}$ in the product of Eq. (17) to obtain

$$\tau = (T_{\mathrm{s}} - T_{\mathrm{H}}) \frac{1}{T_{\mathrm{m}}} \left[1 - \frac{T_{\mathrm{s}}}{T_{\mathrm{m}}} + \left(\frac{T_{\mathrm{s}}}{T_{\mathrm{m}}} \right)^2 - \left(\frac{T_{\mathrm{s}}}{T_{\mathrm{m}}} \right)^3 + \left(\frac{T_{\mathrm{s}}}{T_{\mathrm{m}}} \right)^4 - \left(\frac{T_{\mathrm{s}}}{T_{\mathrm{m}}} \right)^5 + \cdots \right]. \tag{18}$$

Obviously the upper limit of τ is determined by the limit of the expanded Binomial term since the surface temperature is fixed by the characteristics of the collector and the temperature at a height H is in turn fixed by the height. Given fixed values of T_{s} and T_{H} the upper limit is obtained by taking the maximum value of the Binomial series for particular values of T_{m}. Expanding the bracket in Eq. (18) we get

$$\tau = \frac{T_{\mathrm{s}}}{T_{\mathrm{m}}} - \frac{T_{\mathrm{s}}^2}{T_{\mathrm{m}}^2} + \frac{T_{\mathrm{s}}^2}{T_{\mathrm{m}}^3} + \cdots - \frac{T_{\mathrm{H}}}{T_{\mathrm{m}}} + \frac{T_{\mathrm{H}} T_{\mathrm{s}}}{T_{\mathrm{m}}^2} - \frac{T_{\mathrm{s}}^2 T_{\mathrm{H}}}{T_{\mathrm{m}}^3} + \cdots \tag{19}$$

Differentiating Eq. (19) with respect to T_{m} term by term and ignoring terms in $\frac{1}{T_{\mathrm{m}}}$ above second order we get

$$\frac{\mathrm{d}\tau}{\mathrm{d}T_{\mathrm{m}}} = \frac{T_{\mathrm{H}}}{T_{\mathrm{m}}^2} - \frac{T_{\mathrm{s}}}{T_{\mathrm{m}}^2}. \tag{20}$$

$\frac{\mathrm{d}\tau}{\mathrm{d}T_{\mathrm{m}}} = 0$ gives the minimum value of τ when $T_{\mathrm{s}} = T_{\mathrm{H}}$. This is the equilibrium state when the surface temperature equals the temperature at the turbine level. However, the maximum value of τ approaches an asymptotic value as T_{m} approaches T_{s}, that is when T_{m}–T_{s} approaches zero. The physical meaning of this condition is that the temperature of the air mass approaches the temperature of the solar collector surface as heat is transferred from the collector surface to the air mass as can be deduced from Eq. (12). Assuming reasonable typical temperatures for the collector surface, air mass and height as $T_{\mathrm{s}} = 330$ K, $T_{\mathrm{H}} = 313$ K, $T_{\mathrm{m}} = 334.4$ K, we find that $\tau \approx 15$.

Using the value of $\beta(\tau)$ at 300 K and one atmosphere, Eq. (15) is employed to obtain curves shown in Fig. 3 by calculating and plotting the values of P_{i} versus τ for various dimensions of the solar chimney. The curves clearly show that there are specific threshold values of τ beyond which

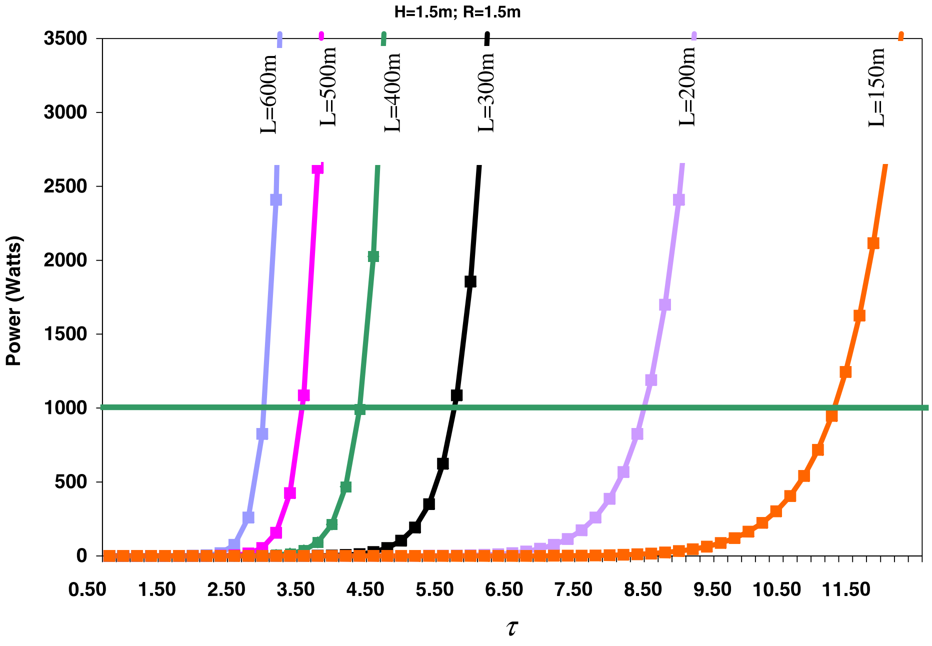

Fig. 3. Curves showing simulated power output for solar chimneys of different lengths when $H = R = 1.5$ m.

appreciable power ($\geqslant 10^3$ W) can be generated by a solar chimney. Furthermore, beyond these threshold values of τ, the power from the chimney increases exponentially.

4. Discussion

As in the case with the voltage–current (I–V) characteristics for different diodes in the forward direction where a threshold voltage V_γ exists beyond which the current rises rapidly, the P_i–τ characteristics shown in Fig. 3 also show that there is a threshold value of τ above which appreciable energy can be generated by a solar chimney.

The curves show that the minimum threshold value of τ beyond which appreciable power (10^3 W) can be generated by a viable solar chimney power generating plant with a square surface of L m is approximately 2.9. Thereafter the power increases rapidly after each threshold value of τ for each specified dimension of the chimney.

The dimensions of a reasonably sturdy solar chimney power plant that would generate energy of the order of 10^3 W, for example, is $L = 150$ m, $H = 1.5$ m and $R = 1.5$ m. This specific dimension requires that $\tau = 10.9$. The length L can be reduced to 50 m provided a value of $\tau = 32.9$ is attained inside the chimney. This is, however far beyond the highest attainable value of approximately 15. If a value of $\tau = 15$ can be attained inside the chimney, a solar chimney power plant of dimensions $L = 150$ m, $H = 1.5$ m and $R = 1.5$ m would generate approximately 4.47×10^4 W.

There are a number of reasons as to why a large area of land must be used as a solar collector. These reasons include the fact that the overall conversion efficiency from solar energy to electricity is 2–3%. There is a temperature drop with altitude of about 10 °C for a 1000 m chimney. Large quantities of warm air have to be lifted from the ground to chimney top which results in gravitational energy loss. The air that leaves the chimney is above ambient temperature at that altitude also resulting in thermal energy loss. As ambient air is drawn into the collector and warmed, expands with little increase in pressure and the majority of solar input is lost in the simple expansion of air before it reaches the turbine [20–24].

5. Conclusion

Solar chimney power stations could make important contributions to the energy supplies in Africa and Asia because more than enough space and sunlight are available in these continents. Although countries such as Sudan, India and Ghana have shown real interest in the technology, all construction plans in these third world countries have not come into fruition due to exorbitant costs. It is therefore inevitable to develop small power generating plants for small-scale industries. The model developed in this paper addresses this issue in detail.

It has been shown in this work that the plotted curves (Fig. 3) for typical solar chimney power plants of various dimensions are similar to the I–V characteristics of various diodes. The curves show that there exist threshold values of the temperature ratios, τ at which significant power ($\geqslant 10^3$ W) can be produced by a solar chimney of specific dimensions. Above the threshold values, τ, the instantaneous electric power increases exponentially. It is thus reasonable to say that to construct and implement a solar chimney power plant to generate appreciable power of practical significance, the temperature ratio τ has to be equal to or greater than 2.9. As the length L of the collector surface is increased and the height H or radius R of the turbine reduced, the power generated by the solar chimney power plant increases as shown in Fig. 3. It is readily deduced that even at 10% efficiency, a solar chimney power plant with the dimensions $L = 150$ m, $H = R = 1.5$ m would produce approximately 4.47×10^3 W which is sufficient to run a small scale industry or serve approximately fifty (50) households in a rural village. The dimensions $L = 150$ m, $H = R = 1.5$ m give the minimum specifications such a solar chimney power plant that would produce appreciable energy for the need stated above.

References

[1] Tiwari GN, Sangeeta S. Solar thermal engineering systems. New Delhi: Narosa Publishing House; 1997.

[2] Sukhatme SP. Solar energy: principles of thermal collection and storage. New Delhi: McGraw-Hill; 1996.

[3] Garg HP, Prakash J. Solar energy: fundamentals and applications. New Delhi: McGraw-Hill; 2000.

[4] Kreith F, Kreider JF. Principles of solar engineering. New York: McGraw-Hill; 1978.

[5] Howell JR, Bannoerot RB, Vliet GC. Solar thermal energy systems. New York: McGraw-Hill; 1982.

[6] Kays WH. Convective heat and mass transfer. New York: McGraw-Hill; 1966.

[7] Kreith F. Principles of heat transfer. New York: Harper and Row; 1973.

[8] Churchill SW, Bernstein MJ. Heat Trans 1977;99:300.

[9] Langhaar HLJ. Appl Mech 1942;64A:55.

[10] http://en.wikipedia.org/wiki/Solar_chimney.

[11] www.math.purdue.edu/~lucier/The_Solar_Chimney.pdf.

[12] Gannon AJ, Backström TW. Solar chimney cycle analysis with system loss and solar collector performance. J Sol Energy Eng 2000;122(3):133–7.

[13] Haaf W. Solar towers, Part II: preliminary test results from the Manzanares pilot plant. Sol Energy 1984;2:141–61.

[14] Haaf W, Friedrich K, Mayr G, Schlaich J. Solar chimneys, Part I: principle and construction of the pilot plant in Manzanares. Sol Energy 1983;2:3–20.

[15] Schlaich J. The solar chimney. Edition Axel Menges. Germany: Stuttgart; 1995.

[16] Schlaich J, Schiel W. Solar chimneys, encyclopedia of physical science and technology. 3rd ed. London: Academic Press; 2001.

[17] Von Backström TW, Gannon AJ. Solar chimney turbine characteristics. Sol Energy 2003;76(1–3):235–41.

[18] Weinrebe G. Solar chimney simulation. In: Proceedings of the IEA solarPACES task III simulation of solar thermal power systems workshop, 28th and 29th September 2000, Cologne.

[19] Weinrebe G. Greenhouse gas mitigation with solar thermal power plants. In: Proceedings of the powergen Europe 1999 conference, Frankfurt, Germany, June 1–3.

[20] Weinrebe G, Schiel W. Up-draught solar tower and down-draught energy tower – A comparison. In: Proceedings of the ISES solar world congress 2001, Adelaide.

[21] Schlaich J. The solar chimney: electricity from the sun. Geislingen, Germany: C. Maurer; 1995.
[22] Von Backström TW, Gannon AJ. Compressible flow through solar power plant chimneys. ASME J Sol Energy Eng 2000;122(3):138–145.
[23] Padki MM, Serif SA. On a simple analytical model for solar chimneys. Intl J Energy Res 1999;23(4):345–9. March 25.
[24] United Nations environmental programme (UNEP). Chemical pollution: a global overview. Geneva: UNEP; 1992.
[25] Incropera FP, DeWitt DP. Fundamentals of heat and mass transfer. New York: John Wiley; 1996.
[26] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York: Spring; 1991.
[27] Welty JR, Wicks CE, Wilson RE. Fundamentals of momentum, heat, and mass transfer. Singapore: John Wiley; 1995.
[28] Benjamin G. Heat conduction and mass diffusion. New York: McGraw-Hill; 1993.
[29] Arthur PF. Heat exchange designs. New York: John Wiley; 1989.
[30] Welty JR, Wicks CE, Wilson RE. Fundamentals of momentum, heat, and mass transfer. Singapore: John Wiley; 1995.
[31] http://groups.yahoo.com/group/awea-wind-home/message/7677.
[32] http://groups.yahoo.com/group/awea-wind-home/message/996.