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Maximum fluid power condition in solar chimney power plants – An analytical approach

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Abstract

Main features of a solar chimney power plant are a circular greenhouse type collector and a tall chimney at its centre. Air flowing radially inwards under the collector roof heats up and enters the chimney after passing through a turbogenerator.

The objective of the study was to investigate analytically the validity and applicability of the assumption that, for maximum fluid power, the optimum ratio of turbine pressure drop to pressure potential (available system pressure difference) is 2/3. An initial power law model assumes that pressure potential is proportional to volume flow to the power m, where m is typically a negative number between 0 and -1, and that the system pressure drop is proportional to the power n, where typically $n = 2$. The analysis shows that the optimum turbine pressure drop as fraction of the pressure potential is $(n - m)/(n + 1)$, which is equal to 2/3 only when $m = 0$, implying a constant pressure potential, independent of flow rate. Consideration of a basic collector model proposed by Schlaich leads to the conclusion that the value of m is equal to the negative of the collector floor-to-exit efficiency. A more comprehensive optimization scheme, incorporating the basic collector model of Schlaich in the analysis, shows that the power law approach is sound and conservative.

It is shown that the constant pressure potential assumption ($m = 0$) may lead to appreciable underestimation of the performance of a solar chimney power plant, when compared to the analyses presented in the paper. More important is that both these analyses predict that maximum fluid power is available at much lower flow rate and much higher turbine pressure drop than predicted by the constant pressure potential assumption. Thus, the constant pressure potential assumption may lead to overestimating the size of the flow passages in the plant, and designing a turbine with inadequate stall margin and excessive runaway speed margin. The derived equations may be useful in the initial estimation of plant performance, in plant performance analysis and in control algorithm design. The analyses may also serve to set up test cases for more comprehensive plant models.

Keywords: Solar chimney power plant; Solar chimney turbine; Solar thermal power plant; Solar tower; Maximum power

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Nomenclature

A	surface area; m^2
C	coefficient
c_p	specific heat; J/kg K
G	solar irradiation; W/m^2
g	gravitational acceleration; m/s^2
H	height; m
K	coefficient
P	power; W
p	pressure; Pa
$\dot{Q}$	heat transfer rate; W
T	temperature; K
V	volume flow rate; m^3/s
*	reference condition

Greek symbols

α	absorption coefficient
β	heat transfer coefficient; W/m^2
Δ	differential
η	efficiency
ρ	density; kg/m^3

Abbreviations

MFP	maximum fluid power
PL	power law

Subscripts

1, 2, 3	coefficient numbers
c	chimney
cfe	collector floor to exit
coll	collector
deck	collector deck
floor	collector floor
L	loss
MFP	maximum fluid power
p	potential
t	turbine

Superscripts

m	pressure potential exponent
n	pressure loss exponent

1. Introduction

In order to design a flow system containing a turbine for maximum power production and to run it at maximum power, engineers need to find the optimal pressure drop across the turbine as a fraction of the total available system pressure difference. The design flow rate through the system determines the size and cost of the plant flow passages as well as the size, design and cost of the turbine. In the design phase some iterative algorithm may suffice to find the optimum, but a simple analytical method would be more convenient in a control algorithm. It could also serve to set up test cases for more comprehensive methods.

Many solar chimney investigators have made the assumption that the optimum ratio of p_t/p_p is 2/3, (Haaf et al., 1983; Lautenschlager et al., 1984; Mullett, 1987; Schlaich, 1995). In more detailed calculations Schlaich (1995) apparently used an optimum value of $p_t/p_p = 0.82$ as evident from the values of p_t and p_p reported in tables. Hedderwick (2001) presented graphs showing values around 0.7. Von Backström and Gannon (2000) used the 2/3 assumption only for optimization at constant available pressure difference, but Gannon and Von Backström (2000) employed an optimization procedure under conditions of constant solar irradiation. Schlaich et al. (2003) reported a p_t/p_p value of about 0.80, while Bernardes et al. (2003) reported a value of as high as 0.97. The wide variation in values warrants further investigation.

The question is the existence or not of a relevant optimum p_t/p_p in solar chimney power plants, and how to determine it. Even under conditions of constant solar irradiation the pressure potential of a solar chimney plant is not fixed but is a function of the air temperature rise in the collector, which varies with flow rate.

The first objective of this paper applies to any general process where the pressure potential is not constant and the system pressure drop is not necessarily proportional to the flow rate to the power 2.0. The objective is to derive simple, generally applicable equations for the determination of the volume flow for maximum fluid power (MFP) and the associated ratio of turbine total pressure drop to pressure potential. The second objective applies to solar chimney power plants. It is to derive equations for finding the optimum flow rate and p_t/p_p conditions as dependent on the relevant design and operating conditions of the plant, using a simple solar collector model.

2. Power law model

The derivation of the power law model requires two generalisations: a pressure potential versus flow relationship and a system pressure drop versus flow relationship. A very simple but useful assumption for the relationship between pressure potential and volume flow is:

$$p_p = K_p V^m \tag{1}$$

where $K_p = p_{ref}/V_{ref}^m$ is determined at a reference point (V_{ref}, p_{ref}) near the optimum, and m is a negative exponent. Fig. 1 shows pressure potential lines for a few values of m. Note that if $m = 0$, then $p_p = K_p$, denoting a constant pressure potential.

A useful assumption for the system pressure drop in incompressible flow is:

$$p_L = K_L V^n \tag{2}$$

where n will typically be 2 when system pressure drop is dominated by minor losses, and closer to 1.75 when the pressure drop is dominated by Reynolds number dependent wall friction losses (White, 2003). The solid line in Fig. 2 represents the system loss curve.

Note that the effect of the variation of density with temperature rise through the system is disregarded, but may be included in the choice of K and n in the vicinity of each operating point. The turbine pressure drop is then:

$$p_t = p_p - p_L = p_p - K_L V^n \tag{3}$$

Since the change in density across a solar chimney turbine is typically ($\Delta\rho_t < 2\%$) we can regard the air flowing through the turbine as incompressible, i.e., the fluid power is equal to the product of the volume flow and total pressure drop across the turbine:

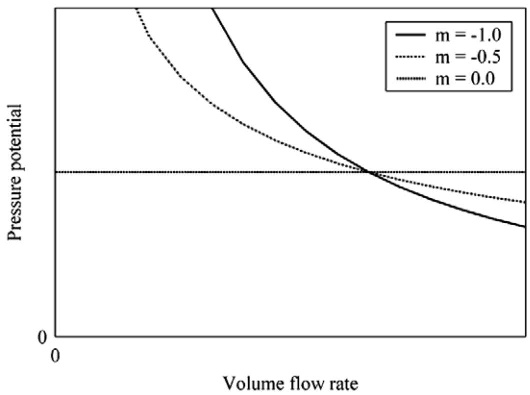

Fig. 1. Pressure potential vs. volume flow for three values of exponent m.

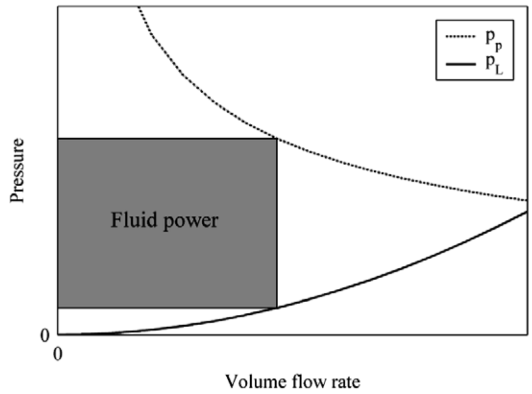

Fig. 2. Plot of pressure potential and pressure loss vs. volume flow, and fluid power (shaded area) for $m = -0.5$.

$$P = p_t V = (p_p - K_L V^n)V \tag{4}$$

The shaded area in Fig. 2 represents the fluid power. The power generation rate of the turbine depends not only on the characteristics of the flow system it is part of, but also on those of the turbine itself. In the present paper, however, we assume that the turbine efficiency does not vary appreciably with changes in flow rate, or, if it does, the variation in turbine losses may be accounted for in the system pressure losses.

2.1. Maximum fluid power condition

The volume flow for maximum fluid power (MFP) is found when $\partial P/\partial V = 0$:

$$\begin{aligned} &\frac{\partial}{\partial V}[(K_p V^m - K_L V^n)V] = 0 \\ &(m+1)K_p V_{MFP}^m - (n+1)K_L V_{MFP}^n = 0 \end{aligned} \tag{5}$$

The flow at maximum fluid power is then given by:

$$V_{MFP} = \left(\frac{K_p(m+1)}{K_L(n+1)}\right)^{\frac{1}{n-m}} \tag{6}$$

Note that when $m = -1$, then $V = 0$ and p_p is infinite, i.e., the power law model is unrealistic at very small flows.

The pressure potential at maximum fluid power follows from substituting Eq. (1) in Eq. (5):

$$(p_p)_{MFP} = \frac{(n+1)}{(m+1)} K_L V_{MFP}^n \tag{7}$$

The turbine pressure drop as fraction of the pressure potential at maximum fluid power is found by subtracting the system loss from the pressure potential:

$$p_t = p_p - K_L V^n$$
$$(p_t)_{MFP} = \frac{(n-m)}{(m+1)} K_L V^n \tag{8}$$
$$\left(\frac{p_t}{p_p}\right)_{MFP} = \frac{(n-m)}{(n+1)}$$

This relatively simple relationship depends on the exponents m and n only. In practice the power law relationship between p_p and V would, for the appropriate values of K_p and of m, approximate the real relationship only in a limited region, but the point where K_p and m are calculated may be adjusted iteratively. The same applies to K_L and n. In time-dependent analyses, a quasi-steady state condition is assumed during the time that the optimum is sought. In practical terms this implies that the turbine configuration (for example the rotor blade setting angles) can be adjusted much faster than plant operating conditions change. The assumption is that during this interval a fixed relationship between the pressure potential and the volume flow exists, or K_p and m are constant, and so are K_L and n.

In the special case when $m = 0$ and $n = 2$, Eq. (6) reduces to:

$$V_{MFP} = \left(\frac{p_p}{3K_L}\right)^{0.5} \tag{9}$$

The MFP flow rate is then $1/\sqrt{3}$ of the maximum flow rate that occurs when $p_t = 0$. Also, when $m = 0$ (p_p = constant) and $n = 2$, Eq. (8) reduces to:

$$\left(\frac{p_t}{p_p}\right)_{MFP} = \frac{(2-0)}{(2+1)} = \frac{2}{3} \tag{10}$$

The MFP condition occurs at $p_t/p_p = 2/3$ only in the special case when $m = 0$ (i.e., constant pressure potential) and $n = 2$. When $n = 2$ and $m \neq 0$, then p_t/p_p for maximum fluid power exceeds 2/3 when m is negative (i.e., pressure potential decreases with volume flow).

3. Value of *m* for simple solar collector model

Consider steady state operation of a solar chimney power plant. The solar collector consists of a transparent deck over a floor that receives solar energy. The collector floor transfers energy to the air flowing over it at the same rate at which it receives energy from the sun, namely at $\alpha G A_{coll}$, where α is the effective absorption coefficient of the collector. The air in the collector loses heat through the collector deck at the same rate that the collector deck loses heat to the environment, namely at $\beta \Delta T A_{coll}$, where β is an adjusted heat transfer coefficient that allows for radiation and convection losses and the fact that the temperature difference between deck and environment increases from 0 at the outer edge of the collector to ΔT at the chimney entrance. The real situation is more complex, but this simple model employed by Schlaich (1995) may be used to derive an approximate expression for the collector temperature rise and the exponent m of the analysis above.

Find the air temperature rise by equating energy entering and leaving the collector:

$$\dot{Q}_{floor} - \dot{Q}_{deck} = \dot{Q}_{cfe}$$
$$\alpha G A_{coll} - \beta \Delta T A_{coll} = V \rho_{coll} c_p \Delta T \tag{11}$$
$$\Delta T = \frac{\alpha G A_{coll}}{V \rho_{coll} c_p + \beta A_{coll}}$$

If the ambient temperature at ground height is T_0, the collector exit (chimney inlet) density is ρ_{coll} and assuming parallel temperature profiles inside and outside the chimney a chimney of height H_c will generate a hydrostatic pressure potential, p_p:

$$p_p = \rho_{coll} g H_c \frac{\Delta T}{T_0} = \frac{\rho_{coll} g H_c}{T_0} \frac{\alpha G A_{coll}}{V \rho_{coll} c_p + \beta A_{coll}} \tag{12}$$

This equation is of the form:

$$p_p = \frac{C_1}{C_2 V + C_3} \tag{13}$$

It can be shown that for a relationship of the form $p = AV^m$, m depends only on the local value of the function and the local value of its gradient, and is given by:

$$m = \frac{dp_p}{dV} \bigg/ \frac{p_p}{V} \tag{14}$$

For a function of another form, for example Eq. (13), an equivalent m can be calculated at any point, since m depends only on the coordinates of the point and its local gradient:

$$\begin{aligned} m &= \frac{dp_p}{dV} \frac{V}{p_p} \\ &= \frac{-C_1 C_2}{(C_2 V + C_3)^2} \frac{V(C_2 V + C_3)}{C_1} \\ &= -\frac{C_2 V}{(C_2 V + C_3)} \end{aligned} \tag{15}$$

Back substitute for C_2 and C_3 and multiply the denominator and numerator by ΔT:

$$\begin{aligned} m &= -\frac{V\rho_{coll}c_p\Delta T}{(V\rho_{coll}c_p\Delta T + \beta A_{coll}\Delta T)} \\ &= -\frac{V\rho_{coll}c_p\Delta T}{\alpha G A_{coll}} \\ &= -\frac{\alpha G A_{coll} - \beta A_{coll}\Delta T}{\alpha G A_{coll}} \\ &= -\frac{\dot{Q}_{floor} - \dot{Q}_{deck}}{\dot{Q}_{floor}} = -\eta_{cfe} \end{aligned} \tag{16}$$

Here η_{cfe} is the net rate at which heat is absorbed by the air between the inlet and exit of the collector, expressed as fraction of the rate of heat transfer from the floor to the air. We shall call it the collector floor-to-exit efficiency since it is a measure of how efficiently the collector transfers heat from its floor to the air leaving the collector. Schlaich (1995) writes the standard collector efficiency for his collector model as:

$$\eta_{coll} = \alpha - \frac{\beta\Delta T}{G} \tag{17}$$

The collector floor-to-exit efficiency can be written similarly by dividing out $\alpha G A_{coll}$ in Eq. (16):

$$\begin{aligned} \eta_{cfe} &= 1 - \frac{\beta\Delta T}{\alpha G} \\ &= \frac{\eta_{coll}}{\alpha} \end{aligned} \tag{18}$$

It is remarkable that in the case of the simplified solar chimney collector model, the exponent m turns out to be simply the negative of the collector floor-to-exit efficiency. The immediate implications are the following:

- m must have a value between 0 and -1
- for $n = 2$, the optimum p_t/p_p is between 2/3 and 1
- the optimal p_t/p_p ratio is 2/3 only if the collector efficiency equals zero.

3.1. Power law vs. constant pressure potential model

A key question is how the value of m affects the prediction of plant power. As a reference condition we use the case where $V = V_{max}/(n+1)^{1/n}$ and $p_t/p_p = n/(n+1)$, and denote it with an asterisk (*). When $p_t/p_p = n/(n+1)$ in the power law model, then from Eqs. (1)–(3):

$$\frac{K_p}{K_L} = (n+1)V_*^{n-m} \tag{19}$$

Substitute Eq. (19) into Eq. (6) to get the volume flow at the MFP condition:

$$\begin{aligned} V_{MFP} &= \left((m+1)V_*^{n-m}\right)^{(n-m)^{-1}} \\ &= (m+1)^{(n-m)^{-1}} V_* \end{aligned} \tag{20}$$

Using Eqs. (1), (8) and (20), the turbine pressure drop at the MFP condition is:

$$p_{tMFP} = \left(\frac{n-m}{n}\right)(m+1)^{m/(n-m)} p_{t*} \tag{21}$$

By substituting Eqs. (20) and (21) into (4), the fluid power at the MFP condition follows:

$$P_{MFP} = \left(1 - \frac{m}{n}\right)(1+m)^{(1+m)/(n-m)} P_* \tag{22}$$

In Table 1, volume flow, pressure potential and power, all at the MFP condition, are listed as a fraction of the respective reference value over a range of collector floor-to-exit efficiencies at $n = 2$ for the power law model. At a collector floor-to-exit efficiency of 70% ($m = -0.70$) we can see that the MFP volume flow may be as low as 64%, the MFP turbine pressure drop may be as high as 185% and the power production may be 118% compared to the reference value. Even at moderate collector floor-to-exit efficiencies of around 50% the optimal turbine pressure drop may be seriously underestimated by using the 2/3 rule.

Schlaich (1995) gives typical values of η_{coll} around 0.55 and α around 0.80, leading to $\eta_{cfe} \approx 0.69$.

Table 1
MFP-values of volume flow rate, turbine pressure drop and fluid power for power law model as a fraction of constant pressure potential model values listed for a range of exponent m ($n = 2.0$)

m	−0.2	−0.3	−0.4	−0.5	−0.6	−0.7	−0.8	−0.9
V_{PL}/V_*	0.904	0.856	0.808	0.758	0.703	0.640	0.564	0.452
p_{tPL}/p_{t*}	1.123	1.205	1.307	1.436	1.606	1.845	2.217	2.963
P_{PL}/P_*	1.014	1.032	1.056	1.088	1.129	1.181	1.248	1.339

Applying the above model we get $m = -0.69$ and from Eq. (8) and assuming $n = 2$ the optimal ratio is $p_t/p_p = (n - m)/(n + 1) = 2.69/3 = 0.90$. This value is much higher than the value of 2/3, and also higher than the value of 0.82 derived from values in a table of data given by Schlaich (1995). On the other hand, a value of $p_t/p_p = 0.82$ corresponds to $\eta_{cfe} = 0.46$, and if $\alpha = 0.8$, to $\eta_{coll} = 0.8 \times 0.46 = 0.37$, which is very low. The value of 0.9 agrees with the value recommended by Bernardes et al. (2003). In his analysis he found optimum values of as high as 0.97, resulting in $m = -0.91$. This would, in combination with his value of collector floor absorption coefficient, $\alpha = 0.9$, imply a collector floor-to-exit efficiency of 0.91/0.9, which exceeds 100%. If the value of 0.8 for α given by Schlaich is replaced by 0.9 in his data set, then $\eta_{cfe} \approx 0.61$, with optimal ratio of $p_t/p_p = 0.87$.

As the tabulated data in Schlaich (1995) were not obtained with a p_t/p_p ratio of 2/3, we cannot apply Eqs. (20)–(22) directly to come up with the values for volume flow, turbine pressure drop and power at the MFP condition. We first have to find the equivalent * condition, by using Eqs. (1) and (2) to get values for K_p and K_L. Assuming these coefficients as well as the exponents m and n to remain constant over a restricted range of flow rate and using the * condition together with Eqs. (1) and (2) from Eq. (19) V_* is:

$$V_* = \left(\frac{3K_L}{K_p}\right)^{\frac{1}{m-n}} \tag{23}$$

The value of m follows from η_{cfe}, and n is taken as 2. We can then find V_* and evaluate p_{p*}, p_{t*}, p_{L*}, and P_*, and find values for the same variables at the MFP condition with Eqs. (20)–(22).

Since n is numerically about three times as large as m, V_* is rather insensitive to the exact value of m. Taking $m = -0.66$ and working with the 100 MW plant data we find that P_{MFP} is 3.7% higher than $P_{Schlaich}$ (for the 30 MW plant it is 3.5% and for the 5 MW it is 3.0%). Changing m by 20% to -0.79 leads to a P_{MFP} that is 8.4% higher than $P_{Schlaich}$, a change of only 4.5%.

4. Effect of variable collector efficiency

The power law model used so far contains an inconsistency: it assumes that m is constant and independent of flow rate, but it then turns out that m is proportional to the collector efficiency, which is in fact a function of flow rate. This limits the power law method to cases where m varies only slightly with flow. The solution is to recognize that the analysis so far does not fully explore the potential of the simple collector model of Schlaich (1995). To find the potential fluid power, while recognizing that η_{cfe} depends on V, we formulate the MFP Coll. model (where the added Coll. denotes the collector): multiply Eq. (12) by V:

$$P = p_t V = \left(\frac{\rho_{coll} g H_c}{T_0} \frac{\alpha G A_{coll} V}{V \rho_{coll} c_p + \beta A_{coll}} - K_L V^n V\right)$$

$$\begin{aligned}\frac{\partial P}{\partial V} &= \left[\frac{\rho_{coll} g H_c}{T_0}\left(\frac{\alpha G A_{coll}}{V \rho_{coll} c_p + \beta A_{coll}} - \frac{\alpha G A_{coll} V \rho_{coll} c_p}{(V \rho_{coll} c_p + \beta A_{coll})^2}\right) - (n+1) K_L V^n\right] = 0 \\ &= \frac{\rho_{coll} g H_c}{T_0}(\alpha G A_{coll}(V \rho_{coll} c_p + \beta A_{coll}) - \alpha G A_{coll} V \rho_{coll} c_p) \\ &\quad - (n+1) K_L V^n((V \rho_{coll} c_p + \beta A_{coll})^2) = 0\end{aligned} \tag{24}$$

If $n = 2$, Eq. (24) is a fourth order polynomial for which an analytical solution procedure exists. Otherwise it has to be solved numerically for $V_{MFP\ Coll}$. It will be more instructive, however, to compare power versus flow graphs for the constant m and variable collector efficiency approaches. Fig. 3 shows that for a 100 MW test case from Schlaich (1995), V_{PL} and $V_{MFP\ Coll}$. are quite similar, but both differ substantially from V_*, the flow at which the turbine pressure drop is 2/3 of the pressure potential. It also shows that use of the 2/3 rule seriously overestimates the maximum flow at which the plant produces any power at all. This value has a

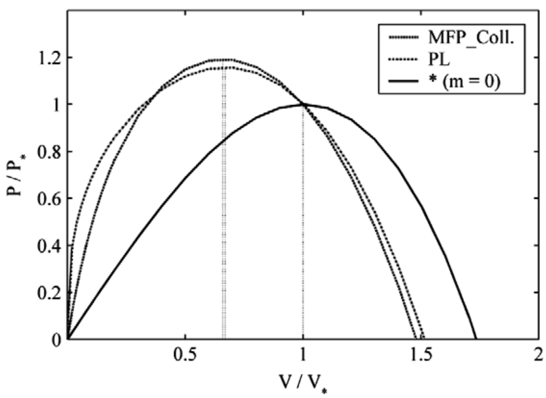

Fig. 3. Plot of fluid power vs. volume flow for various modeling approaches of a 100 MW nominal power plant (normalized by the MFP values of the reference case).

Table 2
Comparison of flow rate, turbine pressure drop and fluid power at the MFP-condition of the power law model and the MFP Coll. model for various power plant sizes as a fraction of the MFP values for the reference case

Nominal power	100 MW		30 MW		5 MW	
	PL	MFP Coll.	PL	MFP Coll.	PL	MFP Coll.
V/V_*	0.659	0.669	0.640	0.643	0.617	0.616
p_t/p_{t*}	1.808	1.730	1.890	1.823	1.996	1.920
P/P_*	1.192	1.158	1.210	1.172	1.232	1.183

large effect on the turbine runaway speed. Table 2 summarizes similar comparisons for the data from Schlaich for several test cases. Typically V_{PL} and $V_{MFP\ Coll}$ are between 67% and 62% of V_*, and the corresponding optimal turbine pressure drops are between 173% and 200% of the values associated with V_*. It is encouraging to see that the simple power law model predicts the maximum power flow within 1% point compared to the MFP Coll. Model in all the test cases and is pessimistic in the prediction of the maximum fluid power value, and optimistic in the prediction of turbine pressure drop.

5. Conclusions

The study developed two analyses for finding the optimal ratio of turbine pressure drop to available pressure drop in a solar chimney power plant for maximum fluid power. In the first part the system pressure potential is assumed to be proportional to V^m where V is the volume flow and m a negative exponent, and the system pressure loss is proportional to V^n where typically $n = 2$. Simple analytical solutions were found for the optimum ratio of p_t/p_p and for the flow associated with it. This ratio is not 2/3 as used in simplified analyses, but depends on the relationship between available pressure drop and volume flow, and on the relationship between system pressure loss and volume flow. The analysis shows that the optimum turbine pressure drop as fraction of the pressure potential is $(n - m)/(n + 1)$, which is equal to 2/3 only if $m = 0$ (i.e., constant pressure potential, independent of volume flow) and $n = 2$. Consideration of a basic collector model proposed by Schlaich led to the conclusion that the value of m is equal to the negative of the collector floor-to-exit efficiency.

The basic collector model is sensitive to the effect of volume flow on the collector efficiency. Its introduction into the analysis indicated that the power law model is conservative in its prediction of maximum fluid power produced by the plant, and in the magnitude of the flow reduction required to achieve this. It was shown that the constant pressure potential assumption may lead to appreciable under estimation of the performance of a solar chimney power plant, when compared to the model using a basic model for the solar collector. More important is that both analyses developed in the paper predict that maximum fluid power is available at much lower flow rate and much higher turbine pressure drop than the constant pressure potential assumption predicts. Thus, the constant pressure potential assumption may lead to overestimating the size of the flow passages in the plant, and designing a turbine with inadequate stall margin and excessive runaway speed margin. The derived equations may be useful in the initial estimation of plant performance, in plant performance analyses and in control algorithm design. The analyses may also serve to set up test cases for more comprehensive plant models.

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