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Technical Note

Low pressure solar thermal converter

Gerald Müller*

School of Civil Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK

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ABSTRACT

The current development of solar power converters with air as working fluid focuses mostly on concentrating collectors combined with hot-air engines, and on very low temperature solar tower concepts. Whilst concentrating collectors and Stirling engines need complex technology, solar tower converters have very low efficiencies and require large installations. Pressurized containers as energy converters offer the advantage of simplicity, but appear not to have been investigated in detail. In order to assess their performance potential, an idealised thermal pressure converter was analysed theoretically. Two improvements to increase the initially low efficiency derived from theory were found. Neglecting losses, maximum theoretical efficiencies ranged from 6.7% for a temperature difference of 60 K to 17.7% for a difference of 195 K. The low pressure solar thermal converter appears to offer development potential for low-tech solar energy conversion.

1. Introduction

Solar energy is an important renewable energy source. A wide variety of technologies to convert solar radiation into useful energy in form of heat or electricity have been developed, see e.g. the overview given in [1]. One particular field, the generation of mechanical power from solar heat using air as the transport fluid, has mostly focussed on two different development strands:

- Concentrating solar collectors and hot-air engines for high temperature differences [2–6].
- Solar updraft towers, which use very low temperature differences, e.g. [7].

The effective operation of hot-air engines requires temperature differences exceeding 600 K and, in case of the Stirling engine, a heat sink (or cold end) [5]. These engines offer good efficiencies, but the required temperatures can realistically only be reached with focusing arrangements. Low Temperature Differential (LTD) engines which operate with working temperatures of 307 K only achieved efficiencies of 0.44% [6]. The solar updraft concept comprises of a transparent roof under which air is heated, a chimney which draws the hot air upwards, and a turbine inside of the chimney. The concept has the advantage of being simple with comparatively small temperature increases of the air in the range of 20–50 K. A prototype was built and operated effectively at Manzanares/Spain. The main disadvantage of the solar updraft concept is the low efficiency. Larger towers are more effective, so that their economy depends on the size of the plant. Fig. 1a shows the principle, Fig. 1b, the efficiency as a function of tower height [7]. It can be seen that even for tower heights of 1000 m, theoretical efficiencies only reach 3.8%.

There is a need for simple, low maintenance, stand-alone solar energy converters for remote areas and/or developing countries. Such a machine would employ air as a working fluid since it simplifies the power conversion considerably. Both development strands described previously can probably not be expected to solve this particular problem.

The continuing interest in the solution of the problem of power generation from solar energy without complex technology is reflected in many suggestions for power converters made in the literature, which even include the power generation by a tethered hot-air balloon [8]. The principle of exploiting the pressure build-up of a heated fluid in a closed container has however attracted little attention; the main reason probably being the perceived low efficiencies. Such converters however potentially have the advantage of simplicity and resulting low costs. This note aims to investigate the theory of the ideal low pressure solar thermal converter in order to determine whether performance/development potential exists. At this stage, only passing attention is paid to the questions connected with the actual construction of such a converter.

* Tel.: +44 2380 592442.
E-mail address: g.muller@soton.ac.uk

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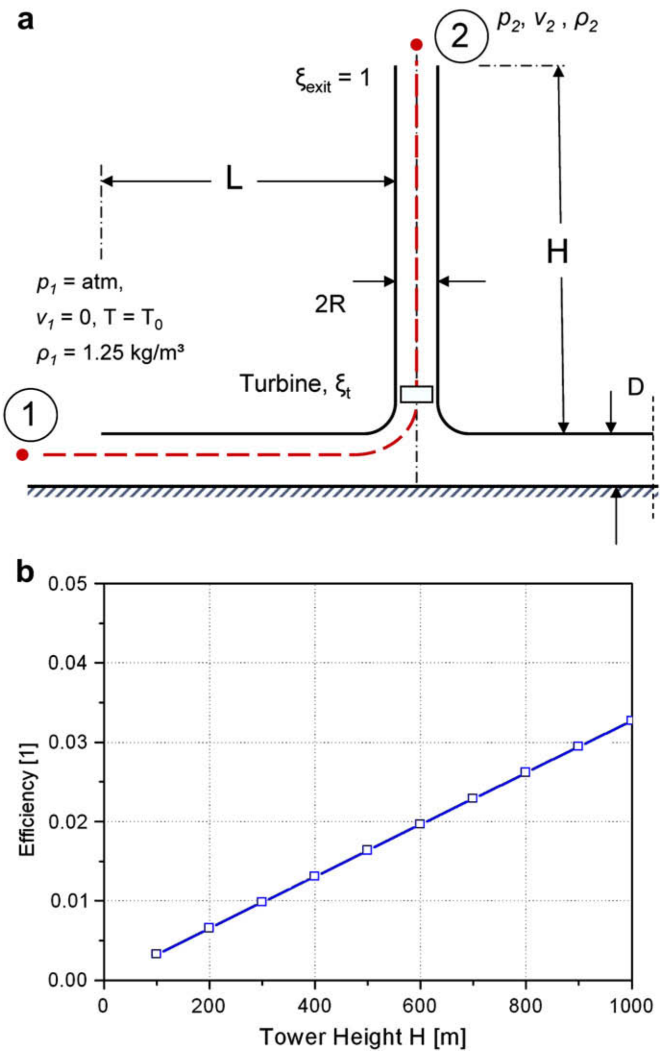

Fig. 1. The solar updraft tower. a. Principle of operation. b. Theoretical efficiency as function of tower height *H*.

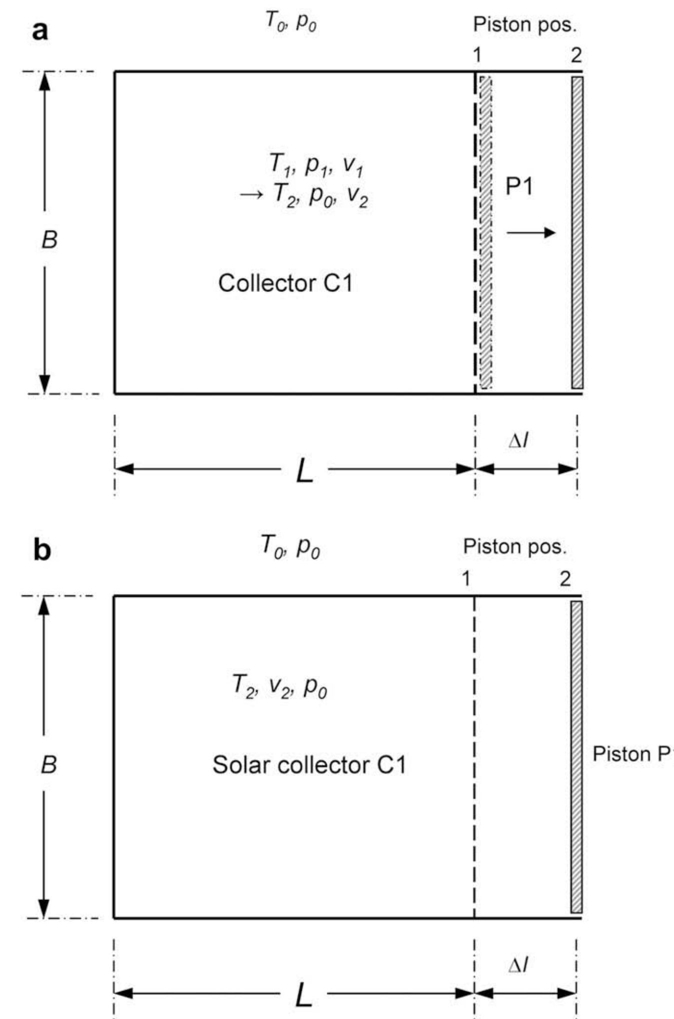

Fig. 2. Solar collector. a. Initial stage and adiabatic expansion. b. Expansion complete.

2. The Low Pressure Solar Thermal Converter (LPSTC)

2.1. Introduction

Most concepts of mechanical power generation from solar energy, even the 'unconventional' ones, focus on the generation of rotational motion [4]. Solar pumps which produce single stroke motion using a variety of different principles were reported, but the potential of pumping action was apparently not explored further [4]. The requirement for rotary motion, which implies a continuous cycle, does however restrict the possibilities of solar power generation. Stepping away from the idea of continuous movement onto discrete motion machines, which generate power with strokes occurring at 'long' intervals, other concepts become possible and problems connected e.g. with time required for mass movement and heat transfer reduces.

2.2. Principle

The idealised LPSTC consists of a collector box, which also acts as a cylinder, with a piston on one side. The surface of the collector absorbs solar energy, whilst the sides and the bottom are insulated, Fig. 2a. The air inside of the collector 'C1' has the initial volume v_0 at ambient temperature T_0, and is then heated up through solar radiation by a temperature difference ΔT to a temperature T_1. The volume $v_1 = v_0$ of 'C1' remains constant, the pressure increases to p_1:

$$p_1 = \frac{T_1}{T_0} p_0 \tag{1}$$

A temperature increase of 120 K results in a pressure of $p_1 = 140$ kPa, assuming $T_0 = 300$ K, $p_0 = 100$ kPa and a mass of 1 kg, corresponding to a volume of 0.861 m^3. Once the operating pressure p_1 is reached, the piston P1 is released and moves backwards to a distance $\Delta l = v_2 - v_1$ until the ambient pressure p_0 is reached again, Fig. 2b. During the adiabatic expansion the volume of the heated air increases from v_1 to v_2, whilst the temperature reduces from T_1 to T_2. The expanded volume of the air can be calculated, with κ as the adiabatic coefficient (air: $\kappa = 1.4$):

$$p_1 \cdot v_1^{\kappa} = p_0 \cdot v_2^{\kappa} \tag{2}$$

With this, the thermal work W_{th} from adiabatic expansion becomes (e.g. [9]):

$$W_{th} = \frac{1}{\kappa - 1}(p_1 \cdot v_1 - p_0 \cdot v_2) \tag{3}$$

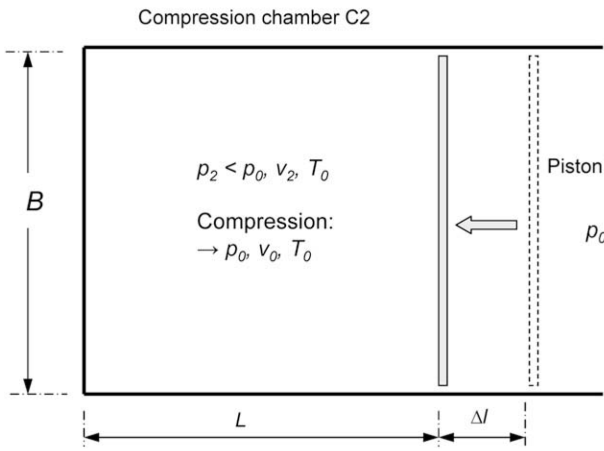

Fig. 3. Atmospheric compression (isothermal).

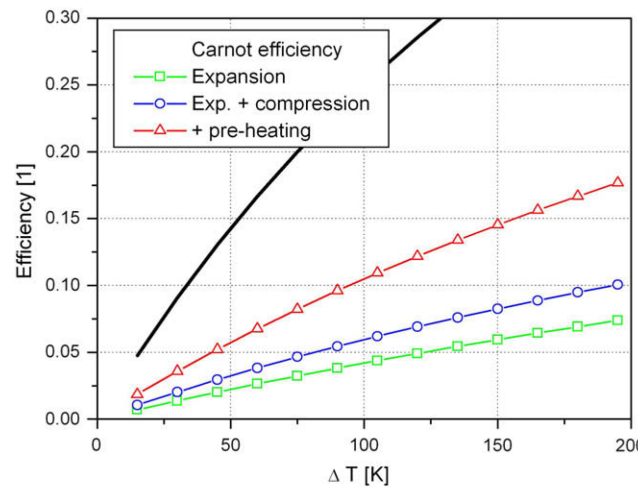

Fig. 4. Efficiencies for simple and improved case.

The actual useable work W_1 is the thermal work minus the atmospheric pressure component:

$$W = W_{\text{th}} - p_0 \cdot \Delta l \tag{4}$$

With an initial pressure of 140 kPa, $\Delta l = 1.096 - 0.861 = 0.235$ m, and the work $P_1 = 4.02$ kJ, whilst the temperature reduces to $T_2 = 381$ K.

In order for the air in the converter to initially reach the operating temperature T_1, the solar radiation must heat up to the air. With a thermal capacity of air $q_v = 0.717$ kJ/kg K (constant volume), the total solar energy E_s required to reach T_1 is:

$$E_s = q_v \cdot (T_1 - T_0) \tag{5}$$

The efficiency η_1 then becomes:

$$\eta_1 = \frac{W_1}{E_s} \tag{6}$$

For $\Delta T = 120$ K, the efficiency only reaches 4.7%.

2.3. Improvement 1: atmospheric work

The efficiency appears to be very low; energy is however still contained in the expanded air volume in form of the temperature difference $\Delta T_2 = T_1 - T_2$. This hot air is assumed to be pushed into a second cylinder C2 (located outside the solar collector), where it is cooled down to ambient temperature, Fig. 3. This results in a reduced pressure p_2:

$$p_2 = \frac{p_0 \cdot v_1 \cdot T_0}{T_2} \tag{7}$$

Once p_2 is reached, the piston P2 is released and thermal work generated. Since continuous cooling can be provided, the atmospheric work W_2 is isothermal

$$W_2 = p_2 \cdot v_2 \cdot \ln(p_2/p_0) + p_0 \cdot (v_2 - v_1) \tag{8}$$

Note that the thermal work is negative in this situation. For an initial temperature of $T_2 = 381$ K, and a volume of 1.096 m^3, this leads to the pressure p_2 to drop to 71.4 kPa (absolute). The isothermal compression work W_2 reaches 2.7 kJ, resulting in an improved efficiency $\eta_1 = 8.0\%$.

2.4. Improvement 2: heat exchange

The temperature of the expanded volume inside the 'cold' cylinder C2 has to be reduced from T_2 to T_0 in order to reduce the pressure. The thermal energy of the expanded air volume v_2 can be employed to pre-heat the new air, which has to be drawn into 'C1' from the atmosphere, from the initial ambient temperature T_0 to T_0':

$$T_0' = \frac{T_0 + T_2}{2} \tag{9}$$

This reduces the energy requirement to reach the initial working temperature T_1 in C1. For $T_0 = 300$ K and $T_2 = 381$ K, the temperature T_0' becomes 341 K. The reduced solar energy E_{red} required to reach T_1 is then:

$$E_{\text{red}} = q_v \cdot (T_1 - T_0') \tag{10}$$

And the improved theoretical efficiency η_2 becomes:

$$\eta_2 = \frac{W_1 + W_2}{E_{\text{red}}} \tag{11}$$

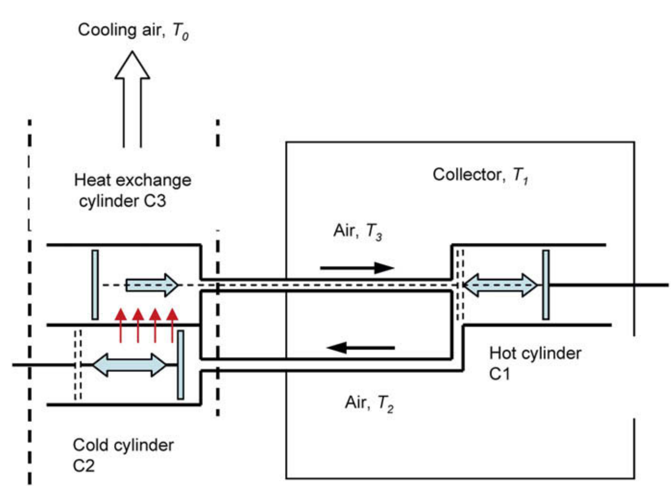

Fig. 5. Schematic of 'real' converter.

This improves the efficiency for $\Delta T = 120$ K from 8.0 to 12.2%; still well below the *Carnot* efficiency of 28.6%.

Fig. 4 shows the efficiencies for the simple and improved cases; added is the *Carnot* efficiency. The efficiencies are significantly higher than those for the solar tower plant, reaching 17.7% for a temperature increase of 195 K.

2.5. The collector and power take-off

A real LPSTC can be envisaged as a 'box inside a box' system where the cylinder is located inside an insulated wall structure with a glass roof. The collector serves as a heat reservoir of (nearly) constant temperature, so that the actual cylinder can be significantly smaller than the collector, Fig. 5. The 'hot' cylinder C1 is connected with the 'cold' cylinder C2, which itself is located outside the collector in a draft chimney. The 'hot' cylinder C1 is heated up from the initial temperature T_0 to T_1. Once the 'hot' cylinder's working stroke has taken place, the air of temperature T_2 is pushed into the 'cold' cylinder C2. Attached to the 'cold' cylinder is the heat exchange cylinder C3, filled with air of ambient temperature which is then pre-heated by the air of temperature T_2 just drawn into the 'cold' cylinder. The temperature in C3 increases from T_0 to T_0' (whilst the temperature of the air in the cold cylinder reduces), the pressure also increases, and the air is then pushed into the 'hot' cylinder C1, to be heated up to the operating temperature T_1. The air in the draft chimney subsequently cools down the 'cold' cylinder to T_0, and its working stroke can occur. C3 and C1 are linked, so that (ideally) no work is required to move the now pressurized air. Numerical simulations showed that even without an external box, temperature differences of 100 K and more are possible [10]. The power generated by the working strokes can be used to pressurize a vessel containing air and water or pump water into a water tower which acts as energy storage; the high pressure water then drives a Pelton turbine. With this arrangement, the discrete motion of the converter can be distributed over time and thus utilized effectively.

2.6. Available power

Assuming a collector area of $A = 25\ \mathrm{m}^2$, and a solar insolation of $1\ \mathrm{kW/m}^2$, the theoretical power maximum (assuming no losses, a converter height of 0.5 m and a temperature difference of 120 K) reaches 3.05 kW for a volume of 12.5 m^3. With a piston volume of 0.861 m^3, ideally one stroke of 0.235 m is required for every 7.6 s.

3. Discussion and conclusions

The manuscript presented a theoretical investigation of a discrete motion low pressure solar thermal machine. The maximum theoretical efficiencies range from 6.7% for temperature differences of 60 K to 17.7% for $\Delta T = 195$ K. These efficiencies are comparatively small, but significantly larger than those reported for the solar chimney. In addition, the proposed collector's efficiency is not dependent on size, so that modular construction becomes possible. The proposed box-inside-a box system implies that the working cylinder constitutes a heat sink, focusing the energy of the collector into it. The technology required is simple and may be cost-effective; it does however require an intermediate energy storage such as a pressure vessel in order to utilise the discrete strokes of the machine. More generally speaking the proposed energy conversion mechanism could possible be termed an atmospheric Stirling cycle.

From the theoretical investigation the following conclusions can be drawn:

- The solar thermal pressure converter constitutes a simple, feasible concept with stand-alone capabilities.
- When an expansion stroke and pre-heating are added, the theoretical efficiencies are acceptable.
- A piston-type solar thermal converter may well have development potential.

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