Solar Electricity using Natural Convection – a research proposal

Abstract

A theoretical configuration is described involving a transparent multichannel chimney above a solar absorber. Beneath the absorber air is drawn from ground level through a nozzle and turbine. An experimental model is proposed of overall height 5m and solar absorber area 3 x 3m with a turbine of diameter 0.4m. Calculation gives maximum air flow velocity of 31.21 ms^{-1} (70 mph) at insolation 750 wm^{-2} and kinetic energy of 2.254 kw with an efficiency of 33.39%.

Outline of Proposal

Consider the configuration shown in Figure 1.

The transparent multichannel chimney is of square cross-section and sited above an efficient solar absorber. Beneath the absorber ambient air flows from ground level through a convergent-divergent nozzle with a turbine sited at the throat of the nozzle. The entire structure stands on 8 legs fixed beneath and around the circumference of the base.

The outer chimney is made of perspex or glass and is transparent down to the level of the solar absorber. The chimney is itself made of 100 equivalent vertical channels of square cross-section and made of thin polythene or other light, strong, transparent plastic.

The solar absorber is made of metal coated with specialist paint that absorbs solar energy with high efficiency. It is suggested that there should be two layers each containing a considerable proportion of open spaces to allow easy upward air flow.

The structure beneath the solar absorber houses a convergent-divergent nozzle and can have an opaque exterior. A vertical axis air turbine is sited at the throat of the nozzle with electrical equipment at ground level.

Solar energy is transmitted with high efficiency through the transparent chimney and partitions to the solar absorber. Here it is taken up with high efficiency by the absorber paint warming its metallic base and air in its neighbourhood. The warmed air rises because it is lighter drawing ambient air to replace through the nozzle and turbine which harnesses the kinetic energy of the air flow exporting it as electricity. The narrower is the throat of the nozzle, the higher is velocity of the air flow and the greater the amount of electricity produced. The removal of kinetic energy by the turbine causes a fall in the temperature of the air flow but this is compensated by the solar absorber.

Guo et al. [1] in their review of progress on the solar chimney consider the importance of the 'slenderness ratio' ie the ratio of the height of the chimney to its diameter. They conclude that for efficient chimney flow a slenderness ratio of 6-8 is optimal.

The present author suggests that a way of achieving optimal slenderness ratio in a chimney of low height would be to subdivide flow in the chimney into many equivalent parallel channels using light but strong partitions [2], [3]. The idea is untested but forms a critical part of the present proposal.

The nett effect of the solar absorber and the transparent multichannel chimney is that solar energy is transmitted downward to the absorber with high efficiency. The absorber converts this energy into rising warm air flow through the chimney. This in turns draws ambient air from beneath the configuration to flow through the nozzle and turbine. A portion of the heat energy in the buoyant exit air can be converted into electricity in the turbine. The lower the diameter of the turbine the higher is the velocity of the air flow and the greater the efficiency of conversion of solar energy into electricity.

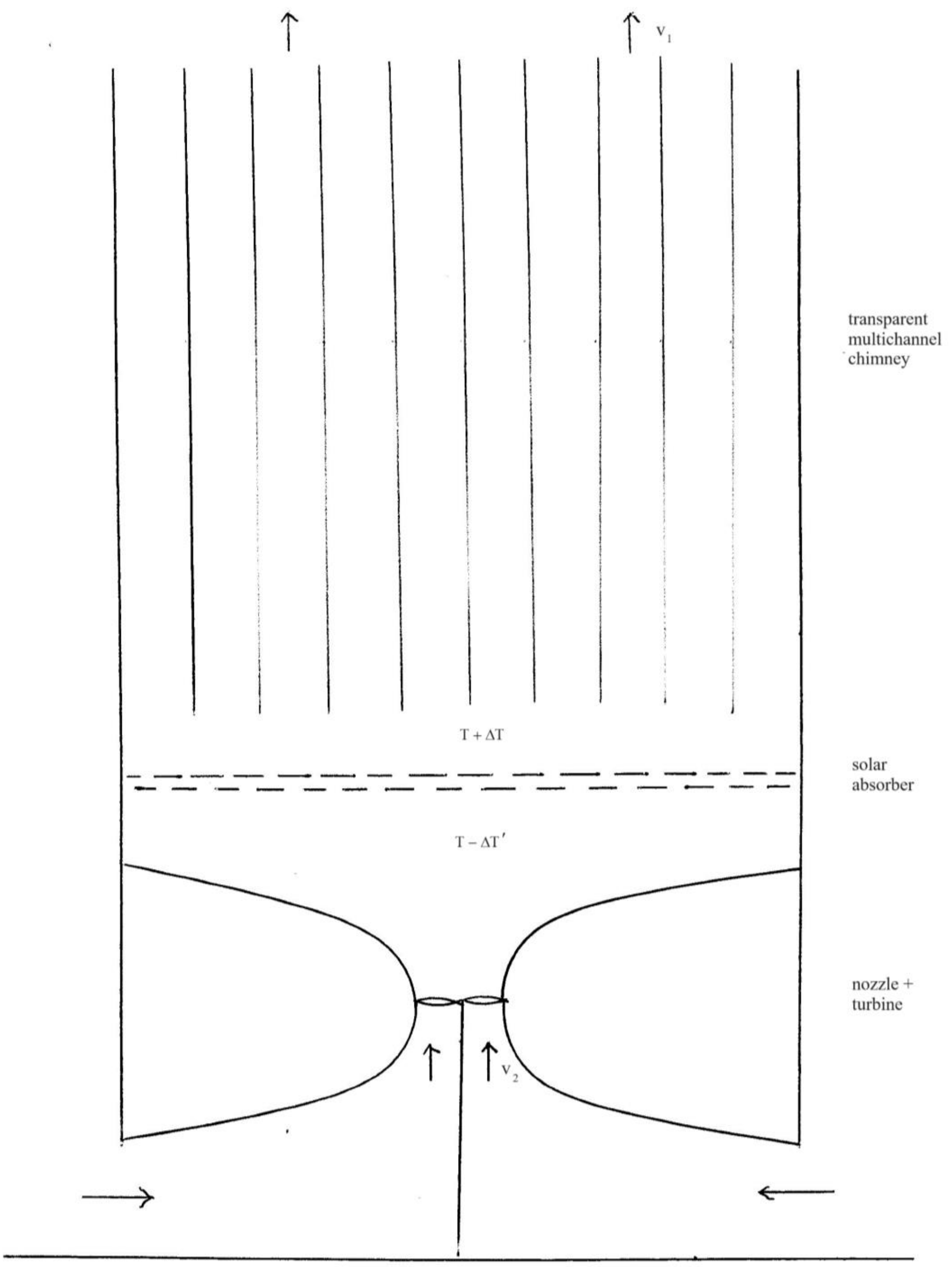

Figure 1

Theoretical Development

Consider that in Figures 1

h	height from solar absorber to top of chimney
A_1	area cross-section of chimney
A_2	area cross-section of turbine
v_1	velocity of air flow through chimney
v_2	velocity of air flow through turbine
T	ambient temperature
ΔT	excess temperature (above ambient) of air flow above solar absorber
$\Delta T'$	fall in temperature of air flow through turbine
g	gravitational constant
ρ	density of air at atmospheric pressure and temperature T
C_p	heat capacity of air at constant pressure and temperature T
I	insolation

The velocity of air flow through the chimney is given by the solar chimney equation [4]

$$v_1^{\,2} = 2 \frac{\Delta T}{T} gh \tag{1}$$

Constant air flow requires that

air flow through chimney = air flow through turbine

$$A_1 v_1 = A_2 v_2 \tag{2}$$

As air flows through the turbine it surrenders its kinetic energy causing a fall in temperature $\Delta T'$

loss of kinetic energy = mass flow x heat capacity x fall in temperature

$$\tfrac{1}{2} \dot{m} v_2^{\,2} = \dot{m} C_p \Delta T'$$

where $\dot{m}$ is the mass flow

$$v_2^{\,2} = 2 C_p \Delta T' \tag{3}$$

As air flows through the solar absorber it must gain temperature by an amount ΔT that provides buoyancy for air in the chimney and by an amount $\Delta T'$ to compensate for the loss in the turbine

total solar energy absorbed = mass flow x heat capacity x temperature rise

$$I A_1 = \rho A_1 v_1 C_p (\Delta T + \Delta T')$$

$$I = \rho v_1 C_p (\Delta T + \Delta T') \tag{4}$$

Equations (1) – (4) describe all the energy changes taking place in the configuration. They contain 7 variables h A_1 A_2 v_1 v_2 ΔT $\Delta T'$ and 5 constants T g ρ C_p I. If 3 of the variables are fixed the algebra is soluble to calculate the other variables. In this way models can be devised and calculations used to assess their practicality.

Experimental Model

Consider in Figure 1 a chimney of height 3m and cross-section 3 x 3m and a turbine of diameter 0.4m. The chimney contains 100 channels of cross-section 0.3 x 0.3m to give slenderness ratio 10.

Equations (1) to (4) apply to the model for which

h	=	3	m	T	=	300	ºK
A_1	=	9	m^2	g	=	9.81	ms^{-2}
A_2	=	0.1256	m^2	ρ	=	1.18	$kg\ m^{-3}$
				C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
				I	=	750	$w\ m^{-2}$

The insolation considered represents summer UK maximum. The entire configuration has an overall height of about 5m.

From equation (1)

$$v_1^{\,2} = \frac{2\ \Delta T}{300} \times 9.81 \times 3$$

$$v_1^{\,2} = 0.1962\ \Delta T \qquad (1)$$

From equation (2)

$$9\ v_1 = 0.1256\ v_2$$

$$v_2 = 71.66\ v_1 \qquad (2)$$

From equation (3)

$$v_2^{\,2} = 2010\ \Delta T' \qquad (3)$$

From equation (4)

$$750 = 1.18 \times 1005\ v_1\ (\Delta T + \Delta T')$$

Using equations (1) (2) and (3)

$$750 = 1185.9\ v_1 \left(\frac{v_1^{\,2}}{0.1962} + \frac{5135}{2010}\ v_1^{\,2} \right)$$

$$v_1^{\,3}\ (2010 + 1007) = 0.6324 \times 0.1962 \times 2010$$

$$v_1^{\,3} = 0.08266$$

	v_1	=	0.4356 ms^{-1}
From (2)	v_2	=	31.21 ms^{-1}
From (1)	ΔT	=	0.9671 °K
From (3)	$\Delta T'$	=	0.4847 °K

$$\text{Maximum kinetic energy} = \tfrac{1}{2}\rho A_2 v_2^{\,3}$$

$$= 0.59\,(0.1256)\,(31.21)^3$$

$$= 2.254 \text{ kw}$$

$$\text{maximum insolation} = 750 \times 9$$

$$= 6.750 \text{ kw}$$

$$\text{Efficiency} = \frac{2.254}{6.750}$$

$$= 33.39\ \%$$

Thus the model considered would have maximum air flow velocity of 31.21 ms^{-1} (70 mph) and maximum output of 2.254 kw. In a warm climate with insolation 6 $kwh/m^2/day$ this would give a daily output of 18 kwh.

Further Comments

- No allowance has been made for energy losses. The major loss is the excess temperature of exit air (ΔT) that is required to provide buoyancy. There will be some loss through the outer wall of the chimney but since the excess temperature is only about 1°C this will be minimal. There will be a significant loss of energy in the turbine but since this is manifested as heat it will contribute to the buoyancy of air in the chimney and is effectively recycled.

- Energy storage can be added using water bottles at ground level [4]. This could take up excess daytime energy for evening and night generation.

- The configuration considered is rectangular but the chimney could be cylindrical and the solar absorber circular. This would have the advantage of easier flow from the mouth of the nozzle into the absorber.

- The model proposed is free-standing and could be built anywhere on open ground. It could alternatively be adjacent to a house or building.

- The model proposed has $h = 3$ and $A_1 = 3 \times 3$. Larger models could be devised with $h = 4\text{-}20$ and proportionately larger solar absorber area and output. A multi-module assembly of larger units could generate electricity on a large scale.

Conclusion

A model vertical configuration is proposed comprising a solar collector and transparent multichannel chimney with a convergent-divergent nozzle to multiply and turbine to harness the kinetic energy of incoming air. An experimental model is suggested with a chimney of height 3m and cross-sectional area 3 x 3m, the chimney containing 100 channels of cross-section 0.3 x 0.3m. It is calculated that a turbine of diameter 0.4m would receive air flow velocity 31.21 ms^{-2} at insolation 750 wm^{-2} generating 2.254 kw electricity with an efficiency of 33.39%.

The calculations are purely theoretical. No experimental work has been carried out on the multichannel chimney or on the model proposed. The author asks experts on the solar chimney and natural convection to consider the proposal critically, to carry out CFD and other theoretical assessment and to build and test the model suggested. If results are successful, much larger models are possible. The goal is that they could provide solar electricity on a large scale at an economic price.

References

[1] P. Guo, T. Li, B. Xu, X. Xu and J. Li. Questions and current understanding about solar chimney power plant : A review. Energy Conversion and Management 2019, 182, 21-33.

[2] www.globalwarmingsolutions.co.uk Multichannel Solar Chimney – dimensions for a demonstration model. July 2020.

[3] www.globalwarmingsolutions.co.uk The Multichannel Solar Chimney – commercial scale. October 2020.

[4] Schlaich, J., Bergermann, R., Schiel, W. and Weinrebe, G. Design of Commercial Solar Updraft Power Systems – Utilization of Solar Induced Convective Flows for Power Generation. J. Sol. Energy Eng. 2005, 127, 117-124.

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