Solar chimney exit loss control by use of a diffuser

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Abstract.

The solar chimney concept relies on the buoyancy of air heated by solar energy to produce an upward air velocity inside a chimney. An air turbine is used to convert the kinetic energy of this air into electricity.

The chimney buoyancy effect is small, requiring chimney height in the order of tens or hundreds of metres for reasonable air velocities to be achieved. Building solar chimneys of this magnitude is an expensive exercise, posing major engineering challenges.

The pressure gradient, created by the solar heating of air before it enters the chimney, is responsible for the kinetic energy of the air. For a chimney with a constant cross sectional area, air velocity is constant up the chimney all the way to the exit. Air velocity at the chimney exit constitutes a loss of kinetic energy. By fitting a diffuser at the chimney end and lowering the exit velocity, this loss can be reduced and the effective pressure difference across the chimney and turbine increased. This paper discusses the potential for pressure recovery in a short solar chimney using an exit diffuser.

A further enquiries concern optimisation the throat area at the air turbine, optimisation of the air turbine itself to maximise efficiency and energy capture and augmentation of output using biomass combustion.

Keywords.

Solar Chimney
Diffuser

1. Introduction.

In 2003/2004 Botswana Technology Centre undertook a preliminary study on solar chimney to assess the viability of using short solar chimney with a nozzle fitted at the turbine to increase the air velocity. Ideally a venturi should have been used instead of a convergent nozzle, as the convergent nozzle introduced exit loss to the system. However, the results were promising as the chimney could actually run the turbine, and hence the objectives of the preliminary study were achieved. The next stage was to optimise the design, based on the results of the preliminary study.

In order to optimise the chimney design, it was recognised that there are four areas of interest to be addressed. These are control of exit loss, optimisation of the turbine design to suit the prevailing conditions inside the chimney, biomass backup and the possibility of using a venturi at the turbine to increase the air velocity (a case of power concentration).

The chimney exit loss control is the subject of discussion of this paper.

2. Description of the solar chimney.

A solar chimney used to generate electricity works on the principle that hot air is lighter than cold air. Solar energy is used to heat air under a glass covered collector. At the centre of the collector the hot air enters a chimney and its buoyancy results in an upward draught. The kinetic energy of the air is converted to electricity using a wind turbine. Figure 1 show the solar chimney installed at BOTEC headquarters in Gaborone. The chimney is 22 m high and 2m diameter made of two flanged glass reinforced plastic (GRP) pipes. The collector area is 15m * 15 m, made of steel frames and 5mm thick ordinary glass. Thermal energy storage is provided by rocks (granite) placed under the collector.

Inside the chimney there is a nozzle 2m high with throat diameter of 1.2m. Installed inside the nozzle is a 1.1m rotor diameter wind turbine.

Figure 1. Solar Chimney Installed at BOTEC headquarters.

The air velocity inside a chimney is calculated using a modified Torricelli equation:

$$v = \sqrt{2gH\frac{\Delta T}{T_h}}$$

Where v is the air velocity, g is gravitational force, H is the chimney height, ΔT is the temperature difference between the hot air inside the chimney and the ambient air temperature and T_h is the hot air temperature.

For a solar chimney of 22m height at 25°C ambient air temperature and 30°C chimney temperature the resulting air velocity is:

$$v = \sqrt{2 * 9.81 * 22 * \frac{5}{303}} = 2.67\text{m/s.}$$

This is hardly adequate for the rated cut-in wind speed of 3m/s for the installed turbine.

Another way of looking at the problem posed by solar chimneys is to consider the chimney efficiency, which is given by:

$$\eta = \frac{Hg}{c_p T_h}$$

T_h is in the order of 300K, c_p is in the order of 1005J/kgK. It therefore follows that since g is only 9.81m/s^2, the chimney height must be in the order of thousands of metres for the chimney efficiency to be of any significant figure.

There is a growing temptation by solar chimney developers to consider building a solar chimney in the magnitude of thousands of metres. Such tall chimneys will not only pose a major engineering challenge but will be too expensive to justify the expense. The alternative is to choose a reasonable chimney height and work around the resulting chimney effect with a view of optimising the benefits.

3. Results from the BOTEC preliminary study.

Figures 2 and 3 show the results obtained from the BOTEC pilot plant. The results were measured from the 22nd of December 2004 to the 4th of January 2005. Figure 1 shows a trend of temperature difference between ambient and collector temperatures, rising from morning to noon and dropping after noon. During the night the temperature difference stays constant as energy is extracted from the rocks. After sunrise, the temperature difference is further reduced due to the fact that the ambient temperature rises faster than the collector temperature due to the thermal mass of the rocks under the collector.

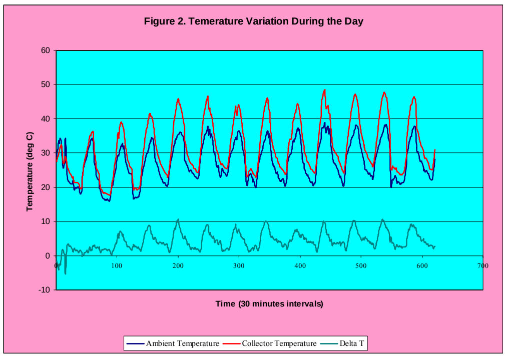

Figure 2. Temerature Variation During the Day

Figure 3 shows that the turbine was running mostly during the day, except during overcast weather. At times the turbine was running during the night, and this was due to wind blowing over the turbine and hence creating suction on the turbine outlet.

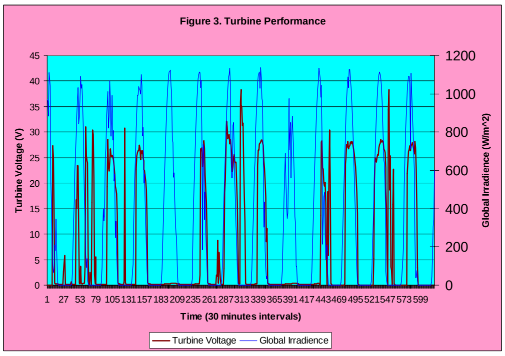

Figure 3. Turbine Performance

4. Short comings of BOTEC study.

The following are the short comings regarding the BOTEC preliminary study:

- No exit loss control: For a cylindrical shaped chimney, the velocity along the chimney is constant all the way to the exit. The exit velocity constitutes a loss given by:

$$P_{tot} = K.E. = \frac{1}{2}mv^2$$

  This loss can be controlled by fitting a diffuser at the top of the chimney to slow down the exit velocity and hence provide pressure recovery, so much needed across the turbine.

- Annulus space between the turbine and the nozzle throat walls: This space was intentionally left to avoid the blames rubbing against the nozzle walls, but seriously affected performance as it provided a part of less resistance for the air to by-pass the turbines.
- Use of convergent nozzle as opposed to venturi: In an attempt to concentrate the

power at the turbine a convergent nozzle was used. For the same reasoning as above, a convergent nozzle also provided its own exit losses due to its abrupt ending. A venturi could have diffused the air velocity after the turbine and hence reduced exit losses.

- Reduced collector area: Due to the high cost of the imported GRP pipes, some of the money intended for the collector was used to purchase the GRP pipes. This resulted in reduced collector area, and hence reduced air temperature.
- Off-shelf turbine: The turbine used in his study was bought off-shelf, with no attempt to modify it to suit the prevailing conditions inside the chimney. This was deliberately done in order to speed up the project.
- Inadequacy of thermal energy storage: Due to the reduced collector area, the amount of energy stored in the rocks provided to be inadequate to run the turbine during the night.

5. Exit loss control.

Like any turbo-machinery, a solar chimney can greatly benefit from the control of the exit losses by using a diffuser. Given the inefficiency of the chimney effect, the need for exit loss control for solar chimneys is even more pronounced.

A diffuser recovers the static pressure of the fluid by decreasing its velocity. Due to possibility of boundary layer separation, the diffusion rate should be limited. It must also be pointed out that a diffuser cannot recover 100% of the pressure as there is energy loss accompanied by the diffusion process.

The equations used for diffuser design are as follows:

$$P_1 + \frac{1}{2}\dot{m}v_1^2 = P_2 + \frac{1}{2}\dot{m}v_2^2$$

$$P_2 - P_1 = \frac{1}{2}\dot{m}\left(v_1^2 - v_2^2\right)$$

$$\dot{m} = A_1 v_1 \rho = A_2 v_2 \rho$$

or $v_2 = \frac{A_1}{A_2} v_1$

The entry velocity to the diffuser is known (from the chimney exit velocity) and this is equal to approximately 2.67m/s average. The diffuser inlet area is also known as this is equal to the chimney exit area.

Arbitrarily choosing the area ration A.R.=5 and inclusion angle of 8^o.

$$A.R. = 5 = \frac{D_2^2}{D_1^2} = \frac{D_2^2}{2^2}$$

$$D_2 = \sqrt{5 * 2^2} = 3m$$

$$A.R. = 5 = \left[1 + 2 * \left(\frac{L}{2}\right)\tan 8^o\right]^2$$

L=8.8m.

$$v_2 = \frac{2^2}{3^2} * 2.67 = 1.187 m/s$$

Without the diffuser the exit loss is:

$$\dot{m} = A_1 v_1 \rho = \frac{\pi * 2^2}{4} * 2.67 * 1.168$$
$$= 9.797 kg/s$$

$$P_{tot} = \frac{1}{2}\dot{m}v_1^2 = \frac{1}{2} * 9.797 * 2.67^2$$
$$= 34.97 N/m^2$$

With the diffuser the exit loss is:

$$P_{tot} = \frac{1}{2}\dot{m}v_2^2 = \frac{1}{2} * 9.797 * 1.187^2$$
$$= 6.89 N/m^2$$

The theoretical diffuser recovery coefficient is therefore:

$$C_p = \frac{34.97 - 6.89}{34.97} = 0.80$$

6. Conclusions and recommendations

The above calculations resulted in a conical diffuser of 2m diameter inlet, 3m diameter outlet and 8.8m length. There is scope to reduce the length by use of diffuser augmentation techniques in order to save on materials. Some of the techniques that can be used include swirl generators, wall suction and exit stagnation plate, just to mention a few. The diffuser can also be improved by consideration of other diffuser shapes such as the bell and trumpet shapes or combination of both.

The existing solar chimney installed by BOTEC did not provide adequate temperature difference due to reduced collector area, and this needs to be improved.

It has also been shown that the amount of thermal energy stored in the rocks is not adequate to run the turbine during the night and other methods of back-up such as use of biomass need to be investigated.

Further improvements can be achieved by purpose designed wind turbine, with the possibility of using venturi to concentrate the power at the turbine.

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