

## Direct Conversion of Wind Energy into Heat Using Joule Machine

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**Abstract.** The small and remote households in Northern regions demand thermal energy rather than electricity. Wind turbine in such places can be used to convert wind energy into thermal energy directly using a heat generator based on the principle of the Joule machine. The heat generator driven by a wind turbine can reduce the cost of energy for heating system. However the optimal performance of the system depends on the torque-speed characteristics of the wind turbine and the heat generator. To achieve maximum efficiency of operation both characteristics should be matched. In the article the condition of optimal performance is developed and an example of the system operating at maximum efficiency is simulated.

**Keywords:** Wind Energy, Wind Turbine, Joule Machine, Heat Generator.

### 1. Introduction

Wind turbines are usually used as movers of electrical generators to produce electricity. A wind turbine is quite simple and efficient source of electrical energy widely used alongside with solar photovoltaic panels for small, remote and isolated households. However such consumers, practically in the Northern regions, demand a significant amount of thermal energy rather than electricity. The energy used for heating of the households can even reach a level of 70% in the total energy balance [1]. Therefore the wind turbines located in such places should be build for thermal energy generation to supply the households by heat in order to reduce the cost of gas or other form of energy used in conventional domestic heating systems. There are a number of applications where mechanical energy produced by wind is indirectly converted into heat through both conventional electrical generator [2, 3, 4] and original magnetic heater [5].

The direct way to convert mechanical energy into heat is based on the principle of the Joule Machine [6]. A heat generator based on this principle is a mixer installed into a tank filled by heat transfer agent (liquid). The shaft of a mixer is rotated by a wind turbine and the liquid is mixed by an impeller. Due to friction among molecules of the mixing liquid, mechanical energy is converted into heat energy. The heated liquid then transfers heat to a heating system. The process comprising the Joule Machine and the Savonius wind turbine, as an example, is shown on the diagram in Fig. 1.

The efficiency of the system “wind turbine – heat generator” depends on speed-torque characteristics of both elements of the system. The optimum performance of the system can be achieved when the speed-torque characteristic of a wind turbine operating at maximum power condition matches the characteristic of the heat generator. In this article the condition of the optimum performance is developed and the simulation of the system operating under maximum power condition is considered. The wind turbine here is considered as a given component of the system but the heat generator is designed to provide required characteristic.

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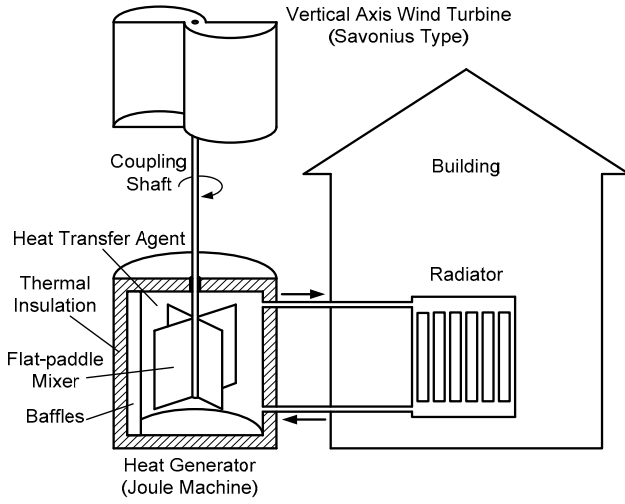


Fig. 1. A diagram of a wind heat generator.

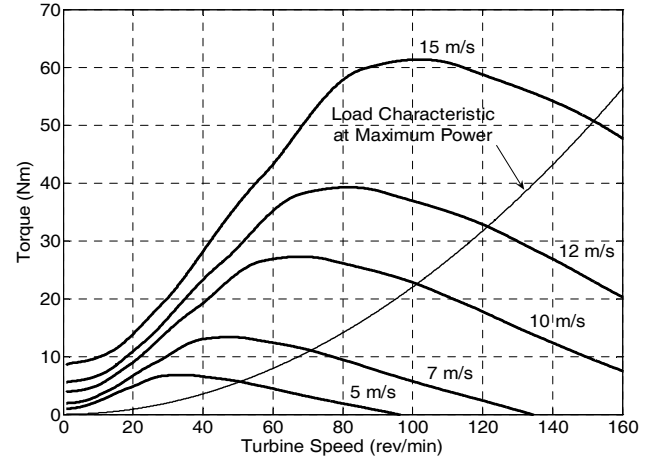


Fig. 2. Family of torque-speed characteristics of Savonius wind turbine at different values of wind speed. The arrow points the torque-speed characteristic of the load required for turbine to operate at maximum power.

## 2. Characteristics of Wind Turbine

A wind turbine of the Savonius type chosen as an example is a vertical axis wind turbine. The turbine operates at a low speed and its tip speed ratio (TSR) does not exceed 1. Savonius wind turbines are usually used for low speed applications such as pumping and very rarely for generating electricity. [7]

The amount of mechanical power produced by a wind turbine depends on the wind speed and the turbine parameters. It is known [8] that power delivered by a wind turbine is

$$P = \frac{1}{2} \rho_A A C_p V^3 \quad (1)$$

where  $\rho_A$  is air density [ $\text{kg/m}^3$ ];  $C_p$  is power coefficient;  $V$  is wind speed [ $\text{m/s}$ ];  $A = 2hR$  is turbine blade area [ $\text{m}^2$ ], where  $R$  is turbine radius [ $\text{m}$ ] and  $h$  is height of turbine rotor [ $\text{m}$ ].

The torque developed by the wind turbine  $T_T$  can be calculated as

$$T_T = \frac{P}{\omega_T} = \frac{\rho_A A C_p V^3}{2\omega_T} \quad (2)$$

The power coefficient  $C_p$  is a function of TSR

$$C_p = f(\lambda) \quad (3)$$

where  $\lambda = \frac{R\omega_T}{V}$  is TSR and  $\omega_T$  is turbine angular speed.

The function  $C_p = f(\lambda)$  is not linear and has maximum  $C_p^{MAX}$  at  $\lambda_E$  as it is shown in Fig. 2. To develop the speed torque characteristic of the turbine the speed of wind  $V$  should be substituted into (2).

$$T_T = \frac{\rho_A A C_p R^3}{2\lambda^3} \omega_T^2 \quad (4)$$

The torque-speed characteristic of the turbine operating at maximum power can be developed from (4) by substituting the maximum value of the power coefficient  $C_p^{MAX}$  and the optimal value of TSR  $\lambda_E$ .

$$T_G = \frac{\rho_A A C_p^{MAX} R^3}{2\lambda_E^3} \omega_G^2 \quad (5)$$

where  $T_G$  is the load torque of the heat generator and  $\omega_G$  is the heat generator angular speed.

The load torque-speed characteristic corresponding to (5) is the target characteristic for designing the heat generator. The Savonius wind turbine chosen as an example has  $R = 0.5\text{m}$  and  $h = 2\text{m}$ . The power

coefficient  $C_p$  of the turbine is  $C_p^{MAX} = 0.195$  at  $\lambda_E = 0.53$ . The family of torque-speed characteristics of the turbine at different values of wind speed are shown in Fig. 2.

### 3. Characteristics of Heat Generator

The heat generator based on the principle of the Joule machine is a mixer which converts mechanical power into heat due to friction loss among molecules of the mixing liquid (Fig.3). Basically, the heat generator consists of a tank covered by thermal insulation, an impeller and a shaft connected to a wind turbine. The tank has a cylinder shape with a diameter  $T$  and height  $H$ . A number of baffles  $z$  with width  $B$  are installed into the tank. The impeller with diameter  $D$  and blade width  $W$  is rotated by a wind turbine. The tank is filled by heat transfer liquid. The heat generator and the vertical axis wind turbine have the same shaft.

The process of mixing with a liquid is described by the following function [9]

$$N_p = f(\text{Re}) \quad (6)$$

where  $N_p$  is the power number,  $\text{Re}$  is Reynolds number.

The power number depends on impeller type and Reynolds number. Also the  $N_p$  can be expressed by

$$N_p = \frac{Pg}{\rho_w n^3 D^5} \quad (7)$$

where  $P$  is the power supplied by the wind turbine to the mixer;  $\rho_w$  is the density of the liquid [ $\text{kg/m}^3$ ];  $D$  is the impeller diameter [m];  $g$  is gravity constant [ $9.81 \text{ m/s}^2$ ];  $n$  is the speed of the mixer shaft [rev/s],  $n = \omega/2\pi$ .

The power number is also a function of number of blades, impeller blade width,  $W/D$  ratio, number of baffles and width of the baffles. Fig. 6 shows the relationship between power number  $N_p$  and Reynolds number  $\text{Re}$  for a six blade flat-paddle impeller with width/diameter ratio of 1/5 [10].

Reynolds number is defined as

$$\text{Re} = \frac{\rho_w n D^2}{\mu} \quad (8)$$

where  $\mu$  is viscosity of the liquid [ $\text{kg/m}\cdot\text{s}$ ].

The process of mixing with mechanical mixer occurs under laminar or turbulent flow conditions. The laminar flow condition takes place at  $\text{Re} < 30$  and fully turbulent condition is achieved at  $\text{Re} > 10000$ . The relationship between  $N_p$  and  $\text{Re}$ , which can be used for both flow conditions, is given by

$$N_p = K \text{Re}^x \quad (9)$$

where  $K$  and  $x$  are constants which depend on the value of  $\text{Re}$ .

Water is chosen as a heat transfer agent to obtain the turbulent condition and high value of  $\text{Re}$  at low rotational speed.  $\text{Re} < 10000$  can be achieved only at very low speed of turbine, about  $10^{-4}$  rev/s. The actual speed of the turbine is much higher. Therefore, it could be found from Fig.6 that for  $\text{Re} > 10000$  and six blade impeller, the constants  $K = 5$  and  $x = 0$ . Thus,  $N_p = K = 5$ . This means that the power number does not depend on the Reynolds number. In this case the load torque has the same quadratic form as required in (5).

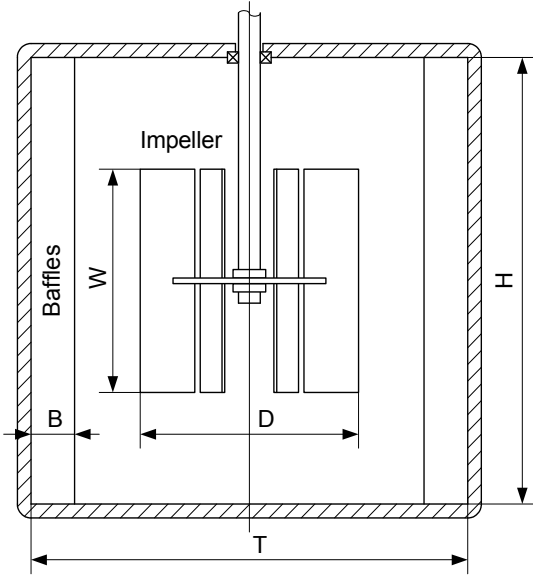


Fig. 3. Design of heat generator

Table 1 Nomenclature of parameters used for simulation

Turbine radius, $R$	0.5 m
Turbine height, $h$	2 m
Maximum of power coefficient, $C_p^{MAX}$	0.195
Optimum STR, $\lambda_E$	0.53
Turbine inertia, $J_T$	1.97 kg·m <sup>2</sup>
Air density, $\rho_A$	1.225 kg/m <sup>3</sup>
Water density, $\rho_W$	1000 kg/m <sup>3</sup>
Water specific heat, $c$	4180 J/kg·°C
Power number, $N_P$	55.62
Heat generator inertia, $J_G$	1.53 kg·m <sup>2</sup>
Impeller diameter, $D$	0.3878 m
Mass of liquid in the tank, $m$	270 kg

$$\frac{Pg}{\rho_W n^3 D^5} = N_P \quad (10)$$

$$T_G = \frac{N_P \rho_W D^5}{8\pi^3 g} \omega_G^2 \quad (11)$$

In (11) the diameter of impeller  $d$  is the only one parameter which can be varied to adjust (11) to (5) to get the required load torque-speed characteristic. Substituting (11) in (5) gives the following equality.

$$\frac{\rho_A A C_p^{MAX} R^3}{2\lambda_E^3} = \frac{N_P \rho_W D^5}{8\pi^3 g} \quad (12)$$

Therefore the diameter of impeller can be found from

$$D = \left( \frac{4\pi^3 g \rho_A A C_p^{MAX} R^3}{N_P \rho_W \lambda_E^3} \right)^{0.2} \quad (13)$$

The diameter of the impeller is a key parameter for designing of the heat generator. (13) shows that the increase in the power number reduces the diameter of impeller and the size of the heat generator.  $N_P$  can be increased by installation the baffles and changing  $W/D$  ratio. The process of mixing is based on an assumption that the main volume of the heat transfer liquid is not mobile. To prevent mobility of the main volume of the liquid, the wall baffles should be installed into the tank. Fig. 5 shows the relationship between  $N_P$  in pu and the baffle size ratio  $zB/T$  [10]. The maximum increase in  $N_P$  1.08pu is corresponding to the baffle size ratio of 0.5. This can be achieved, for example, by installation of 5 baffles with width of 10% of the tank diameter  $T$ .

Most significant increase in  $N_P$  can be obtained by increasing the  $W/D$  ratio. The relationship between  $N_P$  in pu and the  $W/D$  ratio is shown in Fig. 6 [10]. It is found from Fig. 6 that for the six paddle impeller with  $W/D = 1$  the increase in power number is 10.3pu. Therefore, the total increase in the power number for the baffle size ratio of 0.5 and  $W/D = 1$  can be calculated as  $N_P = 5 \cdot 1.08 \cdot 10.3 = 55.62$ .

For a given type of wind turbine, the diameter of the impeller  $D = 0.3878$ m. Using this diameter of impeller, the torque-speed characteristic of the heat generator matches the torque-speed characteristic of the wind turbine and the system can operate at maximum power condition.

The impeller diameter  $D$  and  $W/D$  ratio determine the geometry of the tank. For the given impeller diameter and  $W/D = 1$ , the tank could have a height  $H$  of 0.8m and a diameter  $T$  of 0.8m that gives the

approximate volume of the tank of 270 litres. Therefore, in case if water is chosen as the heat transfer liquid, a mass of the liquid in the tank is 270kg.

During operation of the wind heat generator, mechanical energy converted into heat increases the temperature of the heat transfer liquid in the tank. Under lossless condition, the temperature increase of the liquid  $\Delta T$  is proportional to the energy delivered by the wind turbine to the heat generator and defined by

$$\Delta T = \frac{1}{cm} \int P dt \quad (14)$$

where  $c$  is the specific heat of the liquid [J/kg $^{\circ}$ C],  $m$  is the mass of the liquid in the tank [kg].

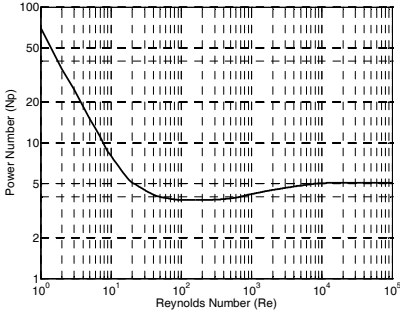


Fig. 4. Power number versus Reynolds number for a flat-paddle six blades impeller with  $W/D$  ratio of 1/5.

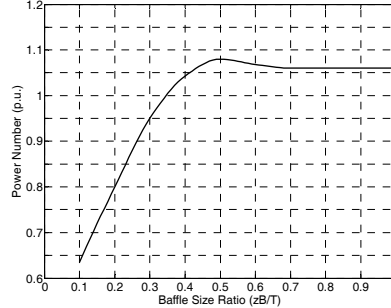


Fig. 5. Power number in p.u. against the baffle size ratio.

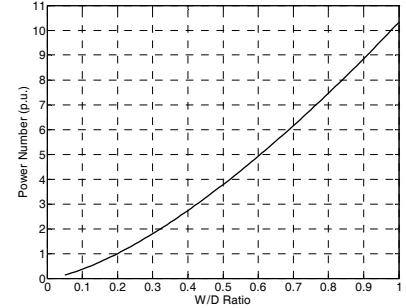


Fig. 6. Power number in p.u. against  $W/D$  ratio.

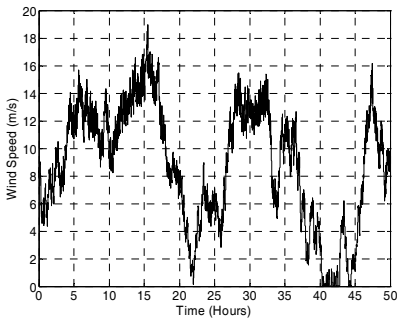


Fig. 7. Wind speed profile for the time duration of 50 hours. The average value of wind speed is 7.5 m/s.

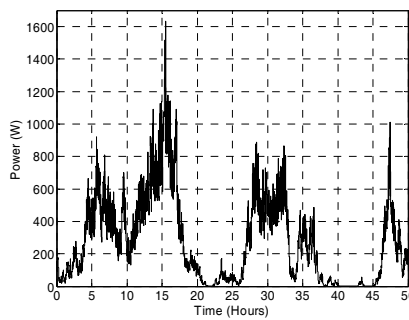


Fig. 8. Power delivered by the wind turbine to the heat generator against time.

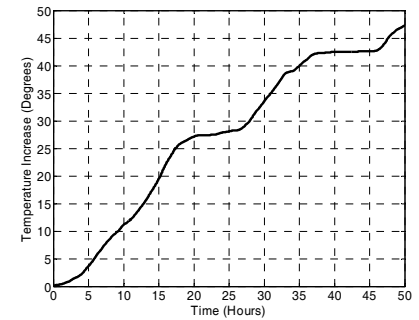


Fig. 9. Temperature increase ( $\Delta T$ ) of the heat transfer liquid against time.

## 4. Simulation

The wind heat generator was simulated using Matlab/Simulink in accordance with (5), (7), (11), (14) and the look-up table of the function (3). The parameters used for simulation is given in Table 1.

An example of wind speed profile, shown in Fig. 7, gives the fluctuation of the wind speed over a duration of 50 hours. The wind profile has significant turbulence and value of average speed (7.5 m/s). It is used in order to simulate the performance of the wind heat generator at low and high wind speeds [11, 12]. The results of simulation under lossless condition are given in Fig. 8 and Fig. 9. It can be seen from Fig. 9, which shows temperature increase of the liquid in the tank, that the higher peak of power, the faster the temperature rising.

## 5. Conclusion

It is shown that wind energy can be converted into heat using wind heat generator (Joule Machine). In order to provide operating of a wind turbine at maximum power condition, the match between the torque-speed characteristics of the wind turbine and the heat generator should be achieved. For a given wind turbine the match is achieved by the diameter of impeller, a general criterion for design of the heat generator.

## 6. References

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