Wind tower based on unexploited industrial chimneys of St. Petersburg

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Abstract. Due to the expansion of St. Petersburg from the beginning of the 20th century, the city has formed a Gray Belt of unexploited factories, some of which are architectural heritage. The modern solution to the problem of the Gray Belt is the creation of lofts and public spaces from them, however, it is also practiced transforming former factories into a site for generating "green energy". Because of the finiteness of the extracted minerals, the use of renewable resources is the most favourable way of producing electricity. The purpose of this work is to consider the possibility of using an industrial pipe to generate energy on the example: one of the highest unexploited pipes in Grey Belt - a steamshop's chimney (100m), built-in 1955. The result of the study is to determine the inexpediency of using the principle of a wind tube in chimneys in the Gray belt in St.Petersburg, because, based on the calculations, according to the developed method, the height required for the wind turbine to start moving is 154m in the summertime in St. Petersburg. During the consideration of the highest pipe in the Leningrad Region (320m), there was concluded that it can provide electricity for 31 people.

1. Introduction

At present, cities are developing at a high rate, including St. Petersburg, but it so happened that the historical centre of the city is surrounded by the so-called "Grey Belt" (Fig.1). The "Grey belt" is hundreds of hectares of land that used to be occupied by industrial enterprises but now they are decommissioned due to the expansion of the city. They can be converted into residential areas and business centres. However, because the once used industrial plants are the architectural heritage of the city, they cannot be demolished, and one of the possible options for using unexploited towers from these factories is to equip them for wind power [1].

The current socio-economic situation in various countries of the world and its development trends show a steady increase in electricity consumption. Also, the problem of our society is the problem of maintaining a safe state of the environment for the life of various living organisms. Therefore, many studies are being carried out in the field of using renewable sources of generating energy - such as wind power, hydropower, etc., in particular, the use of a wind tower.

One of the possibilities for the use of unexploited pipes of factories in the Grey Belt is their reconstruction of power towers that use wind energy due to the pressure drop at the base of the tower.
and at the outlet - the so-called wind towers. A similar technology is being implemented in solar towers, which additionally use the increase in pressure at the base by heating the air in the greenhouse before entering the pipe (Fig. 2). However, at the considered plant there is no place to install a large greenhouse around the pipe, besides, in St. Petersburg we experience insufficient sunlight, therefore this article considers the option of using the pipe without designing a greenhouse [2].

![Figure 1. St. Petersburg’s Grey Belt [1].](image1)

![Figure 2. Air flow diagram in a solar tube [3].](image2)

The plant with one of the highest chimneys within the Grey Belt of St. Petersburg, which is 100 meters high and with the diameter equals to 8m is considered in this study. This is the chimney of a non-working steamshop. For a long time, it was not used in any way, and they were going to demolish it, but they could not do it due to the fact that it is in the Grey Belt. In 2011, enthusiasts breathed life into it with a "graffiti party" there. And now a street art museum is actively working in its workshops. This object continues to develop, but the pipe remains a simple unused "candle", and this article examines its possible use. For comparison, the highest chimney in the Leningrad region was also considered - from the Kirishskaya GRES, the height of which is 320 m, and the diameter is 25 m [4,5].

2. Materials and methods

With the help of an empirical method and analysis, the operation of a wind tube is based on the phenomenon of a temperature gradient, i.e., from the decrease in air temperature with height. This means that the energy efficiency of such an installation depends on its height. The situation is considered for the average temperature of the coldest month - January - 266.4K and for the average temperature of the warmest month - July – 291.3K in St. Petersburg [6].

Temperature gradient - the amount of temperature change per unit length in the direction of heat propagation, i.e., in the direction normal to the isothermal surface. Expressed in Kelvin per meter (K/m) or in degrees Celsius per meter (°C/m) [7].

Due to the temperature gradient, a thrust effect is formed, as a result of which air masses move from the high-pressure area to the low-pressure area, due to the heating of the air at the base of the pipe and a decrease in temperature to the top. In this paper, a decrease in temperature with an increase in height every 100m by 0.6K in wintertime and 0.9K in summertime (because in summer temperature gradient is more than in winter) is considered [8,9].
Table 1. Condition of consideration.

| №  | Name                              | Symbol | Unit | Data | Comment                      |
|----|-----------------------------------|--------|------|------|-----------------------------|
| 1  | Height of tower                   | $h_1$  | m    | 100  | Street art museum’s tower   |
|    |                                   | $h_2$  | m    | 320  | Kirishskaya GRES’s tower    |
| 2  | Intern diameter of tower          | $d_1$  | m    | 8    | Street art museum’s tower   |
|    |                                   | $d_2$  | m    | 25   | Kirishskaya GRES’s tower    |
| 3  | Temperature gradient              | $dT$   | K    | 0.6  | In wintertime                |
|    |                                   |        |      | 0.9  | In summertime                |
| 4  | Temperature near the ground in St.| $T_0$  | K    | 266.4| In January                   |
|    | Petersburg                        |        |      | 291.3| In July                      |
| 5  | Absolute air pressure             | $P_a$  | Pa   | 101300| For St. Petersburg [6]      |
| 6  | Minimum working speed of turbine  | $V_{\text{min}}$ | m/s | 2.5 | [10]                         |

The design scheme is shown in the figure 3.

Figure 3. Design scheme of the wind tower and speed distribution inside the tube.

Analysing formula of airflow capacity can calculate wind tower’s power $P$, W [11]:

$$P = n \cdot \rho \cdot V^3 \cdot S / 2$$  \hspace{1cm} (1)

where $n$ is the wind energy utilization rate, equals to [12]:

$$n = 0.9 \cdot 0.8 \cdot n_{FSC}$$  \hspace{1cm} (2)

where 0.9 – coefficient for friction and kinetic losses for wind chimney, 0.8 – combined efficiency of the air turbine, gear box and electric generators, $n_{FSC}$ – maximum efficiency for wind chimney, equals to [12]:

$$n_{FSC} = \frac{g \cdot h}{C_p \cdot T_0}$$  \hspace{1cm} (3)

where $g$ is the acceleration due to gravity, $g = 9.8 \text{ m/sec}^2$, $h$ – height of tower, m, $C_p$ - heat capacity of air, $C_p = 1005 \text{ J/(kg*K)}$, $T_0$ – temperature near the ground, K.

$\rho$ from formula (1) is the air density on the top of a pipe, kg/m$^3$, equals to:
\[ \rho = \frac{p_a}{RT}, \]  

where \( p_a \) – absolute air pressure, Pa, \( R \) – specific gas constant, \( R = 287 \text{ J/(kg*K)} \), \( T \) - air temperature at the top of the pipe, K.

\( v \) from formula (1) is the speed of the air flow through the wind turbine, m / s, \( S \) is the cross-sectional area of the pipe, m\(^2\), equals to

\[ S = \pi \cdot \frac{d^2}{4}, \tag{5} \]

The formula (1) shows that the power depends on the cube of the speed and the cross-sectional area. The speed in the heat pipe depends on the temperature difference, which is obtained from the Bernoulli theorem:

\[ p + \rho \cdot g \cdot h + \frac{\rho \cdot v^2}{2} = \text{const}, \tag{6} \]

Taking the energy difference at the base of the tower and at the height \( h \), the velocity value can be calculated by the formula:

\[ v_h = \sqrt{2 \cdot g \cdot h \cdot \left(1 - \frac{T}{T_0}\right)} \tag{7} \]

where, \( v_h \) is air’s velocity on the top of the tower. Taking into account the fact that every 100 meters on average the air temperature changes by \( dT \), the final temperature \( T \) is equal to [9]:

\[ T = T_0 - \frac{h}{100} \cdot dT \tag{8} \]

Considering friction and kinetic losses according to the [12] we have formula:

\[ v_h = \sqrt{2 \cdot g \cdot h \cdot \left(1 - \frac{T}{T_0}\right) / ((k + 1) \cdot a)} \tag{9} \]

where \( k \) – friction loss coefficient inside the wind chimney, equal to:

\[ k = k_{in} + 4 \cdot C_d \cdot h/d \tag{10} \]

where, for the operation range of Reynolds numbers inside the wind chimney, the drag friction factor \( C_d \) is approximately equal to 0.003 and \( k_{in} \) is estimated to 0.15 [12].

\( a \) from formula (9) is kinetic energy correction coefficient, of a usual value of 1.058 [12].

3. Results and discussion

Calculations were performed using formula (9). The values of the velocities and powers of the wind tower are calculated. The results are shown in Table 2 as well as on the Figures 4,5.

| № | Name                                | Tower             | Symbol            | Value  | Unit |
|---|-------------------------------------|-------------------|-------------------|--------|------|
| 1 | Velocity on the top of the wind tower | Street art museum | V1, summertime    | 1.6    | m/s  |
|   |                                     |                   | V1, wintertime    | 1.37   | m/s  |
|   |                                     | Kirishskaya GRES  | V2, summertime    | 5.13   | m/s  |
|   |                                     |                   | V2, wintertime    | 4.38   | m/s  |
2 Capacity of the wind tower | Kirishskaya GRES | P2, summertime | 23.2 kW
| P2, wintertime | 31.3 kW

| Figure 4. Air velocity (m/s) dependence by height (m) for different diameters and temperature gradients.

| Figure 5. Capacity (W) dependence by height (m) and diameter (m).

It can be seen from the figure 4 that the grey belt tower’s height of 100 meters is not enough to start the wind generator. The higher temperature gradient, the higher final velocity. The diameter on does not influence a lot on the internal velocity. The minimum height for wind tower operation is 180 meters in winter period and 154 meters in summertime.

It can be seen from the figure 5 that Kirishskaya GRES’s tower could reach 23.2 kW in wintertime if it used wind tube technology, and 31.3 kW in summertime.

According to [13], annual average people’s consumption in Russia equals to 0.75 kWh, so Average energy consumption of 10 people in Russia equals to 7.5 kW. It is clear from the Figure 5 that using wind tower technology on the highest tube in St. Petersburg in wintertime would be enough to cover all expenses in energy of at list 31 people in Russia.

4. Summary
As a result of the study, a method was developed for calculating the parameters of a wind turbine (velocity and capacity) for pipes of different heights.

The formula is derived and graphical dependences of the air velocity at the exit from the pipe are obtained depending on the height and diameter of the pipe, surface air temperature, and temperature gradient.

According to the developed methodology, it was concluded that the height of one of the highest pipes in the Gray Belt (100m) in St. Petersburg is insufficient for the implementation of the wind tube technology because the height of the pipe is not large enough for the airflow to accelerate the wind turbine to the starting speed.

When considering the highest pipe (320m) in the Leningrad Region, it was revealed that the introduction of wind pipe technologies in such a structure will help provide 31 people with electricity.

5. References
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