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Micro Geothermal Generation Device

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ABSTRACT

There are many places in the world where one has access to very high temperature water effluents and at the same time access to very cold water. This happens in many SPA thermal resources in the high mountains. The usual solution to generate electricity for those cases, if one doesn't want to drill wells, is using the hot source and the cold sink to install an Organic Rankine Cycle (ORC) power plant. This might be a very good solution but usually expensive and complicated to maintain and operate. In this paper a very practical, simple, novel design is presented where the water from the hot spring is connected to a tube where vacuum is produced by a Torricelli pipe. The incoming hot water under vacuum will split in low pressure steam and hot water at the corresponding saturated temperature. The steam flows upward and passes through a simple design axial turbine connected to a generator. The exhaust steam is sent laterally to another vertical pipe that acts as a direct contact barometric condenser, cooled with cold water from a flowing stream. Since the system itself has a small enthalpy jump, running between low and very low steam pressures, special care is made in the design to avoid as much as possible heat and pressure losses. The design of the axial vertical steam turbine involves several interesting features; the rotor and the diaphragm are printed in 3D using a special plastic. The turbine parts (fixed and rotating) are inserted in a steal pipe. The trust bearings are made of *sintered* metal in oil, allowing constant lubrication. The main characteristics of a 5 kW generation plant is presented and the benefits for distributed generation are highlighted.

1. INTRODUCTION

There are many geographically isolated places where there exist hot springs. In this paper most of the effort is concentrated in finding a practical, simple and inexpensive way to make use of this heat to transform it into electricity. A few kW of electricity might be a significant improvement for isolated villages in the high mountains or the coast, as it happens in Mexico. Instead of using diesel generators to have electricity a few hours for illumination, TV or running a pump, such as the case of Maguatichic in the Chihuahua mountains in the northern Mexico, Sanchez (2005), or in the beautiful beaches of Baja California with hot water at a few meters depth as in Santispac or places where hot (boiling) sea water is directly pouring to the sea as in Puertecitos where people actually support their needs with small wind generators or solar PV panels that charge a battery to use the electricity when needed, Aguilar-Jiménez, (2018). It is easy to imagine the change in domestic habits when renewable electrical energy is supply in a constant way, day and night during the whole year. The geothermal opportunities in Mexico are quite big, Hiriart (2017).

With constant electricity supply, refrigeration can be introduced allowing a drastic change in the pattern of consumption, finding out that the best is to have a constant demand. With geothermal electricity nothing is saved turning off the supply; one has some sort of perpetual electricity as long as the hot spring keeps flowing. No water is consumed, one only extracts heat from it before it dissipates to the atmosphere. As we have insisted in this study, simplicity is the name of the game. Part of it is running the plant at constant load, without pretending to regulate the consumption, dissipating energy with a rheostat or a few bulb lamps when having low demand.

Another important application could be a resort that makes use of the hot springs for health treatment promoting it as an ecologically friendly place, generating its own electricity using the heat of the water. Again, it makes a lot of difference for an isolated place, to have constant electricity, as in the solution presented here, or having it from diesel, solar or wind.

The main idea of this paper is to present all the steps of the design of a 5 kW Geothermal Micro Generator (GMG) using 100°C water as a constant source at the inlet and 20°C water as cooling media; the prototype will be tested first with air (the turbine) and the rest of the equipment with real geothermal hot water in our facility in Guanajuato.

In this paper we present the description of the components of the flash condensing cycle used in the GMG and show calculations of heat and mass balance to determine the optimal design conditions. Then we present the simple design for a steam turbine capable to work between low and very low pressure concentrating the effort in the thermodynamics of the design. Perhaps the most valuable and challenging part of this research was the mechanical design of the turbine; the idea, as explained later, was to fabricate the turbine using additive manufacturing with appropriate plastic materials. We printed in 3D with plastic the turbine in a local factory in Queretaro State in Mexico. One important feature of choosing additive printing as manufacturing method is that the diaphragm, moving and fixed blades can be printed in one block; i.e. it is not necessary to manufacture the ring of diaphragms and the one of fixed blades in two pieces; it is printed entirely in one piece. It was also very important to find the right material for the thrust bearings; in this case we use a quite new technique, at least for us, of self-lubricating sintered bearing. Finally, we highlight the small, simple details that were study to reduce all the heat losses and to improve the thermal efficiency cooling the system with its own working fluid (i.e. steam).

We believe that improving with time the basic ideas of the simple machine here presented and including industrial design technique to make it more friendly and nice looking, one can have practical solution for distributed renewable energy to help satisfy many needs of isolated regions regardless of the economic restraints of the final consumer.

2. DESIGN OF THE GEOTHERMAL MICRO GENERATOR (MGM)

2.1 Conceptual

In order to make possible the application of this particular GMC we must start from having a constant source of very hot water (hopefully close to 100°C). The water source can be a natural hot spring or separated water of an industrial process or even from a very shallow well, as it happens in some mining activities. We also need a source of cold water to be used in the condensing process. All our design will be oriented to a 100°C hot spring, as the one we have in Guanajuato, where we are developing a classical geothermal field.

The basic of the process of the GMG is that hot water (close to 100°C) enters in the lower part of a vertical tube (1) where vacuum is generated in order to reduce the pressure and to obtain steam at this pressure, this could be accomplished by a at (2). The steam is passed through an axial vertical turbine, that exhausts laterally to a vacuum tube where very low pressure is accomplished by a direct contact condenser where cold water (close to 20°C) enters to the water sprinklers (3) and leaves the system at (4) with its corresponding Torricelli tube or a vacuum pump, as shown in the Figure 1.

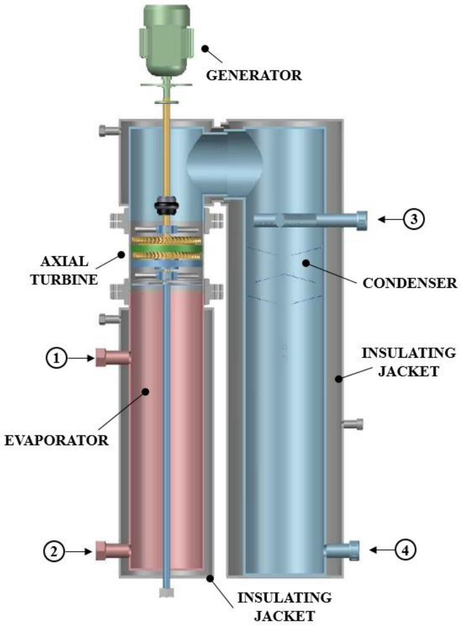

Figure 1: Conceptual design of the 5 kW Geothermal Micro Generator.

The generator is located in the upper part, coupled to the turbine. In our case we are using, for simplicity, a DC generator that will run at constant electrical load (thus constant velocity)

2.2 Energy and mass balance

The model of a single flash is performed, based on the steady flow analysis of the processes. The kinetic and potential energy changes are small relative to the work done; thus they are neglected. The devices are assumed to be well insulated so the heat losses to the external media are not considered.

Baseline parameters of the heat and mass balance were selected as:

- Inlet temperature hot side – 100°C
- Evaporator pressure – 0.4 bara
- Power Generation – 5.5 kW
- Turbine efficiency – 20 %
- Condenser pressure – 0.1 bara

Mass an energy balances for each component of the cycle can be expressed by:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

Where $\dot{m}$, $\dot{Q}$, $\dot{W}$ and h, are mass flow rate, neat heat, work input, and specific enthalpy, respectively. The subscripts *in* are used for the inlet and *out* for the outlet of the component.

The properties of the geothermal fluid along the cycle were computed with REFPROP, considering pure water without non-condensable gases. The heat and mass balance results are shown in Figure 2.

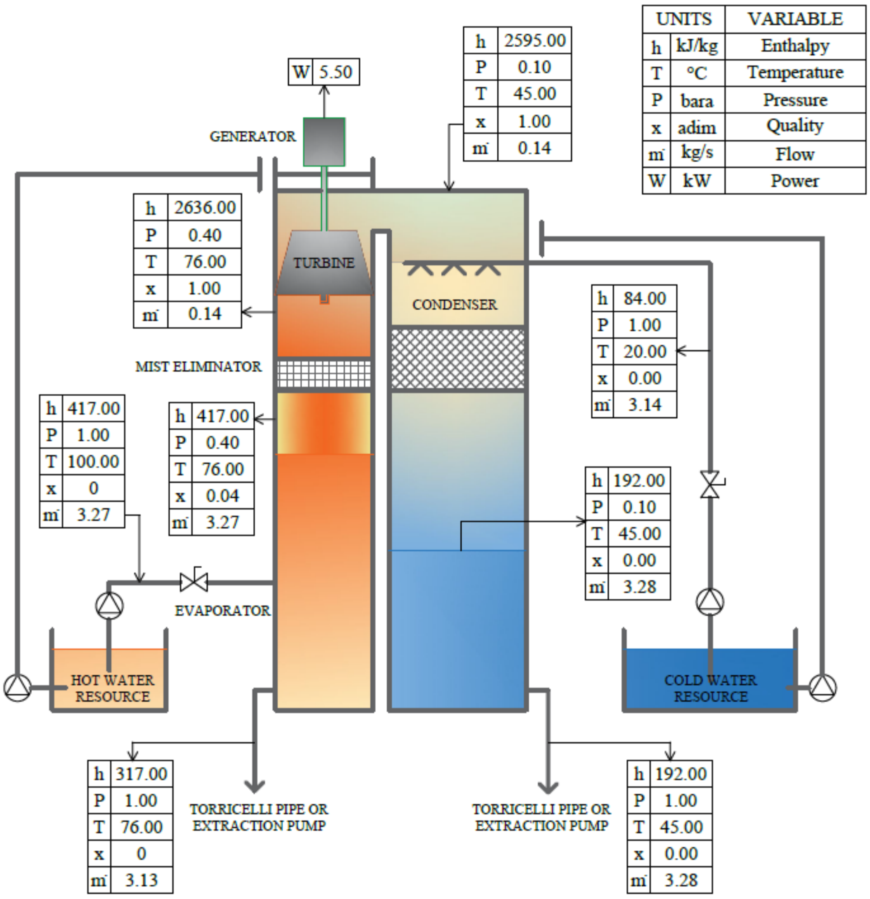

Figure 2: GMG Heat and mass balance.

2.2.1 Optimization

The design parameters were selected *a priori* as the most suitable, based on previous work with similar components, with the purpose of improving the performance of the GMG equipment computations were made to determine the best operation point of the system. The evaluation reference is the hot water consumption respect to power generation [C], varying the pressure on the evaporator [P_{evap}] and condenser [P_{cond}] side, results are shown in Figure 3.

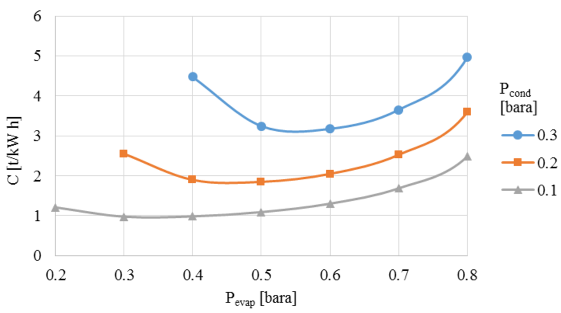

Figure 3: Hot water consumption per kWh for different evaporation/condensation pressure values.

The lowest hot water consumption from the geothermal reservoir is between the pressure of 0.3 and 0.4 bara on the evaporator side and 0.1 bara on the condenser side. The design parameters are not considerably far from the best operation point, considering that, a higher configuration or extra auxiliary power consumption will be needed in order to generate a lower level of vacuum pressure, the design parameters remain the same.

3 INCREASING THERMAL EFFICIENCY

The following topics were addressed in order to avoid all the losses in the system:

Starting with the equipment distribution, the turbine is placed just over the evaporator body reducing the pressure loss on the steam line, the same principle is followed for the exhaust line having the condenser very close to the exhaust. Both, the evaporator and the condenser will be fabricated with standard steel pipes of 12 and 14 inch diameter.

The evaporator will be covered with an insulating jacket, filled with the same hot water (100°C) used for steam generation. The exhaust steam line and condenser will be covered in a jacket with circulating cooling water (20°C). This will not only work as an insulating method, but also the liquid film could act as a seal on atmosphere contact parts, preventing the air inlet and vacuum pressure rupture, seals are one of the most challenging topics on the turbomachinery design, for this particular system the minimum loss of pressure could result in a drastic drop of power.

4 DESIGN OF LOW PRESSURE STEAM TURBINE

We designed our own turbine adapted for the particular requirements of the system; relative small diameter to be installed in a 24" pipe, relatively low turning speed in order to be directly coupled to a generator, able to work with very small pressure difference, always with the objective of simplicity in mind.

The first step was the selection of the turbine type we will work on, the configuration options were Radial inflow, Radial outflow, Axial, single or double stage, following the recommendations of Balje (1981), based on the specific speed and diameter, the right option was a partial admission axial turbine.

The Curtis turbine configuration was implemented to reduce the steam velocity at the outlet, and avoid the supersonic steam speed, since exceeded the local sound velocity will create shocks. An axial turbine is less common in micro applications, allows more compact design and lowest rpm for reasonable efficiency, Novotny et al. (2019).

The model of the turbine is based on energy and mass balance of point 2.2, the principle of the calculation follows the methodology of Kearton (1992), the rpm, the mean diameter, the power output, and de pressure drop where the starting point for the turbine characteristics definition. The model was built based on an iterative routine made in Microsoft Excel, the velocity triangles were drawn, and the losses are estimated using the empirical correlations given by Kearton (1992), some details were completed with field experience.

The blade height of small steam turbines is extremely low when steam is admitted in a full arc, to avoid losses due to low blade height, partial admission is commonly adopted. This configuration causes additional losses because of the periodically pass of the blades through both admitted and unadmitted arcs, Sakay, et al. (2006). The initial approach was inclined to a partial admission turbine and remains the same even considering the risk of the losses increase, in order to permit a longer blade height.

The partial admission of the turbine will be fixed, only the calculated admission area of the diaphragm will have nozzles, the flow regulation will relate on a simple throttle valve because the philosophy if this design is to install the turbine at the site and calibrate it to work full load and to keep it always as such. This is done having a constant electrical load (dissipating energy when necessary).

The main results and design properties of the turbine model are shown below, a 10% extra power was considered for the design value preventing the future mechanical or electrical losses.

Tab. 1: Resulting design parameters of the turbine

Diaphragm vanes outlet angle (α_1)	20.	[°]
First row rotor blades inlet angle (β_{11})	21.9	[°]
First row rotor blades outlet angle (β_{12})	24.8	[°]
Deflector vanes outlet angle (α_{11})	25.2	[°]
Second row rotor blades inlet angle (β_{21})	26.1	[°]
Second row rotor blades outlet angle (β_{22})	30.9	[°]
Mean diameter (d)	265	[mm]
Diaphragm vanes length (l_1)	15	[mm]
First row blade length (l_2)	20	[mm]
Deflector vanes length (l_3)	22	[mm]
Second row blade length (l_4)	30	[mm]
Number of stator/rotor blades (for full admission)	50	[1]
Partial admission (*e*)	43	[%]
Partial admission segments (*i*)	3	kW

Tab. 2: Nominal performance parameters

Inlet steam pressure (P_0)	0.4	[bara]
Outlet steam pressure (P_1)	0.1	[bara]
Rotation speed (N)	3600	[rpm]
Steam flow rate ($\dot{m}$)	0.2	[tph]
Efficiency (η)	43	[%]
Shaft power	5.5	kW

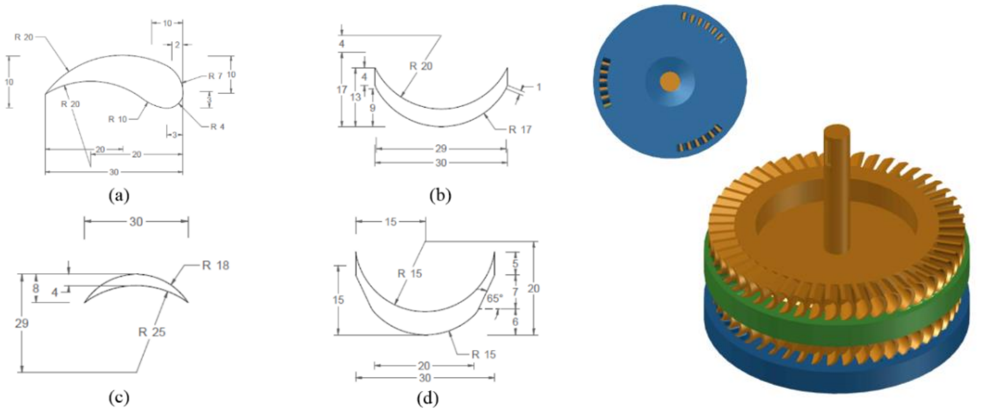

Figure 4: Detail of Diaphragm vane (a), First row rotor blade (b), Deflector fixed vane (c) and Second row rotor blade (d); Isometric 3D view of Diaphragm, Rotor and Stator, and bottom view of the partial admission diaphragm.

4.1 MANUFACTURING

Project early investigations suggested that it may be possible to manufacture the turbine with 3D computer printing, that is with additive manufacturing. This is a method that allow us to quickly transform three-dimensional computer-aided design (CAD) data to a scale model or to a prototype.

The particular characteristics of the GMG allow the possibility of manufacturing the principal turbine parts with additive manufacturing, the most remarkable benefit of working with additive manufacturing is the possibility of printing the rotor and stator as single pieces instead of individually blades to be assembled, this simplifies the design work and will drastically reduce the assembling time.

There are several methods of additive manufacturing, Stereolithography (SL, commonly known as SLA®), Plastic Laser sintering (LS), Selective laser sintering (SLS®), Fused Filament Fabrication (FFF), fused deposition modelling (FDM®) or material extrusion, Direct metal laser sintering (DMLS®), selective laser melting (SLM®), laser (metal) powder bed fusion (LPBF), Metal Binder Jetting (MBJ), Electron-beam melting (EBM) and wire deposition (EBWD), among others. Is important to highlight that the surface finish of parts fabricated with additive manufacturing requires post-processing according to the project-specific needs, there are more additive manufacturing methods but the mention ones are suitable ones for turbomachinery applications, further details were described by Novotny et al. (2019).

Additive manufacturing technologies are limited also by the maximum working or printable space of the machines, our design is in the edge of the dimensional capacity of the selected technology, Selective Laser Sintering (SLS®). The technology selection process was limited by the available methods in our country (México), the specialist of the manufacturing chosen company help us to adapt the design and select the right method and material for the case.

The material selected for the printing process was Nylon 12 PA, it shows excellent surface resolution details, good chemical resistance, and relatively high strength and temperature resistance. Other materials were considered for the manufacturing as Quadrant EPP Ketron© GF30 PEEK-Extruded 30% Glass-Reinforced Polyether Ketone (PEEK-GF30), and Acrylonitrile Butadiene Styrene molded (ABS), its mechanical properties were evaluated by Hernandez-Carrillo, (2017).

The remaining elements of the turbine can be easily manufactured by conventional manufacturing methods, or are standard prefabricated items, the casing, bearings, bearings supports and the coupling for the generator axis are metallic. The bearings, thrust, and radial were selected as self-lubricating sintered bearings. The sintered material can be impregnated with lubricant oil, and the oil film between the axis and bearing forms as soon the system start run, and remains in the sintered metal pores while standing by. The bearings do not require additional lubrication oil nor maintenance, its operation live is shorter but contribute with the simplicity of the system, the heat generated by friction will dissipate with the circulating steam.

Assembling the turbine its really simple compared with classical steam turbines, the vertical configuration and the 3D printing manufacturing method allow a few steps assembling processes, the casing, fabricated of standard pipe was modified with a level to support the diaphragm and the fixed (not rotating) parts are screwed to the casing wall. The bearing casings are welded to the support and the casing wall. The final design is shown below (Figure 5).

The turbine will be assembled to the whole system with flange ends welded to the turbine casing, which, as was mentioned earlier is made of modified standard pipe, this configuration offers easy access to the turbine and the possibility of change all components in a single operation.

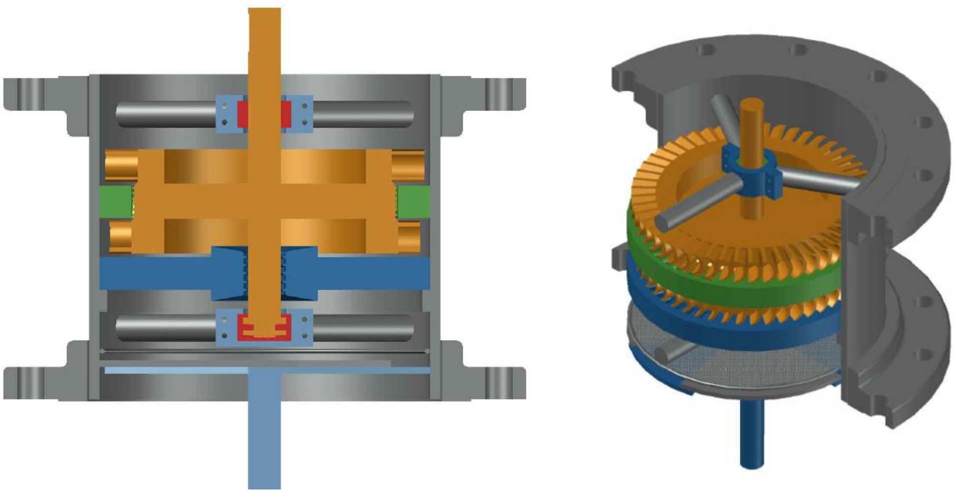

Figure 5: Cut out section of the complete turbine, casing isometric view.

5 CONCLUSIONS AND FUTURE WORK

The conceptual design and the corresponding heat and mass balance of a simple power plant to generate electricity using a hot source of very high temperature (100°C) and a cold (20°C) cooling stream have been presented. The amount of hot and cold water needed to generate 5 kW were determined, also the optimum pressure for the inlet and exhaust were presented

A small 5 KW steam, axial, vertical, Curtis turbine was designed. Its main parameters were set in order to fit the turbine inside a 12” inch pipe and to run at constant load and speed. The option of try with a different turbine configuration (i.e. radial), still present for future development.

The turbine was built in a 3D printing facility in Querétaro, Mexico. A selected plastic (Nylon) that supports the reasonable (75°C) temperature of the turbine. A complete analysis for selecting the right material was presented. The main feature highlighted in the paper is that the fixed and rotary parts of the turbine are printed in one block. That allows assembling the turbine inside a pipe (stator) without cutting it. Details of this method were presented.

The bearings of the vertical (impulse) turbine were made of sintered material embedded with oil for permanent lubrication. This is presented as an experimental solution for a case like this. Special details of the design of the whole plant to avoid, as much as possible, the heat and pressure losses were described.

The turbine will be first tried with air and the assembled to be tested with real geothermal hot water in Guanajuato, and with certain adaptations the GMG could bring renewable electricity to isolated regions using hot and cold water, when available at the site, with a simple power plant, and a very inexpensive steam turbine, easy to operate and to maintain.

Figure 6: Early geyser exploration for future GMC installation in Guanajuato, México.

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