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OPTIMIZED EXHAUST DUCT APPLIED IN THERMOELECTRIC WASTE HEAT RECOVERY SYSTEM

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Abstract. *With following world demand for electricity and increasing scarcity of natural energy resources, it is imperative to search for alternative methods for electricity production or increasing the efficiency of existing processes. The use of Seebeck modules (TEG) have been shown the green output of power cogeneration using waste heat energy. Furthermore, the overall conversion efficiency by this system is about 5%, a factor that discourages the high costs embedded. This work aims to seek increased efficiency in thermal-electrical conversion indeed by TEG, starting from a geometry optimization of hot gases exhaust duct. The distance between each TEG and surface was varied lengthwise to flow, creating a thermally resistive air layer, and from a heuristic optimization process, good results about equalization on surface temperature was found by finite element simulations. A low surface temperature gradient allows TEG work closely to maximum efficiency condition and distant of mechanical failure.*

Keywords: *Geometry optimization, Thermoeletric efficiency, Recovery System, Waste energy.*

1. INTRODUCTION

Approximately 60% of the energy consumed in the world is rejected as heat as shown by Incropera (2011). About 40% of these are heats above 200°C (DOE, 2006). In this sense, Thermoelectric Generators (TEG) offer a potential application in the direct conversion of heat into electrical energy. It is a solid device that promotes direct conversion of heat (from waste-heat sources), from a temperature gradient into electrical energy based on the Seebeck effect. This technology discovered by Thomas Seebeck in 1821 was responsible for several benefits. This is a very reliable and silent system (no moving parts), simple, compact, light and capable of operating at high temperatures (Tervo and Manninen, 2009).

The major disadvantage is the relatively low conversion efficiency (typically 5% (Ismail and Ahmed, 2009)) which has restricted this application for specific uses where reliability is more important than the applied costs. Because it is a well accepted technology in the green environment, there is a broad of people, especially in the scientific community, interested in the expansion of this efficiency. Generally, the thermoelectric electricity cost comprehend the device cost and the operating one. In the use of hot gases from heat generator exhaust, operating costs are neglected, because the incoming energy (fuel) costs is cheap or free.

Therefore, one important reason to study thermoelectric generation using wasted heat, is to reduce the cost per watt from the device (Ismail and Ahmed, 2009). The cost per watt can be reduced essentially in four ways: by optimizing the device geometry (gas output duct), improving the quality and construction process, operating at high temperature gradients or improving and discovering materials with high thermoelectric power (Figure of Merit Z) as represented by expression (1) below, that means both a high Seebeck coefficient (S), low thermal conductivity (k) and high electrical conductivity (σ) (Ismail and Ahmed, 2009).

$$Z = \frac{\sigma S^2}{k} \tag{1}$$

As Z goes to infinity, the thermoelectric generator efficiency approaches to the maximum thermal efficiency given by the Carnot cycle.

Large part of renewable energy sources innovations were focused on the discovery and development of new materials.

New alloys have been researched, some using nanotechnology. In 2009 studies reported the construction of a composite material using nanotechnology-structures, Cerium-Ytterbium, which achieved a efficiency close to 25% (Ismail and Ahmed, 2009).

It is evident the necessity of academic work, in other to increase the cost per watt of this technology, focusing not only in the development of new materials studies. In the last three decades, several works have attempted to design an effective thermoelectric generator. Some works in the automotive industry succeeded with enough generated energy that they were able to replace the electric alternator (Saqr and Musa, 2008) and (Palacios, 2002). Some of the research focused on exploring new thermoelectric materials can be found by Nissan (Kern, 1972) and Porsche (Munekiyo, 1998) research centers.

Moreover, other studies focused on developing effective thermoelectric geometries to ensure a good utilization of the exhaust heat were well succeed (Saqr and Musa, 2009). It was shown that the high efficiency of the exhaust ducts geometry is to provide sufficient area to build the thermoelectric modules and to keep the exhaust gas speed at a big value. Maintaining high exhaust speed, ensures that the heat transfer coefficient by convection correspondingly high.

Another important finding, not substantiated yet, is related to the decrease in the surface temperature difference between the inlet and the outlet of the catchment area.This difference, when increased, makes the power supply unstable in the thermoelectric modules. In (Menze, 1994), an innovative project of thermoelectric cogeneration in a 2.0L V6 motor vehicle is presented by the authors. In (Hartnett and Bergles, 1998), with a geometry analysis studies the performance of the exhaust duct heat exchanger is validated by numerical simulation of mass and heat transfer with comprehensive study of Computational Fluid Dynamics (CFD), in which several positive results are delivered to the academic environment. The results of this simulation were compared with the ones done by Nissan in (Bejan and Kraus, 2003). It is clearly shown that the optimization of the geometry has significantly increased the thermal performance of the systems reviewed.

Genetic algorithms was used by (Belanger and Gosselin, 2011) to simulate the behavior and optimize the use of modules in cross-flow heat exchanger. The study determined the effect of the amount, heat exchanger modules location and non-uniform temperature distribution.

Furthermore, they were not found any other works that relate optimization by heuristic methods with simulation in Finite Elements in this field. This information gap can hide many performance gains from cogeneration energy.

2. METHODOLOGY

The physical problem can be assessed at Fig. 1 and 2. The Fig. 1 introduce the p-n structure of the thermoelectric module with load. The Fig. 2 show the convection heat exchange in the hot fluid, conduction in the duct shell and TEG, and convection with the external environment (ambient air).

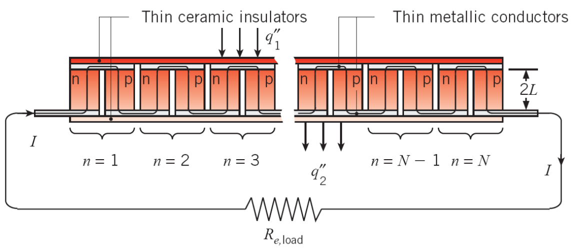


Figure 1: The p-n structure of the thermoelectric module with load Incropera (2011).

For a 1 kW electric power generation plant were elected 42 high performance TEG (Thermonamic, 2013). Considering the maximum length of 500mm duct, the best solution found was a hexagonal geometry, with 6 rows containing 7 TEG each, as shown at Fig. 3 and Table I.

As reported by Saqr and Musa (2009), the duct pickup device must include sufficient area for TEG positioning and promote the maintenance of the temperature gradient in the longitudinal surface of the duct. From an analysis of a real electrical generator system with exhaust temperature approximately 500°C, the pickup duct must contain a limited longitudinal length of 500mm. From this value, large temperature gradients in the longitudinal flow axis were observed, both in experimental and finite elements. Aiming to reduce this gradient, it is recommended that TEG occupy the shortest length constructable.

As proposed in Saqr and Musa (2009) and Belanger and Gosselin (2011), in order to equalize the surface temperature on uptake duct, it was proposed some changing in the longitudinal internal geometry, great thickness and higher heat resistance at the entrance and lower thickness and thermal resistance at the output.The goal of this sample is to find a relationship between the temperature variation of the hot gas exhaust with the varying thickness, to maintain the surface temperature at lowest possible gradient. This construction is shown at Fig. 4.

Obtaining the best thickness for null gradient surface becomes an optimization problem which parameters to be opti-

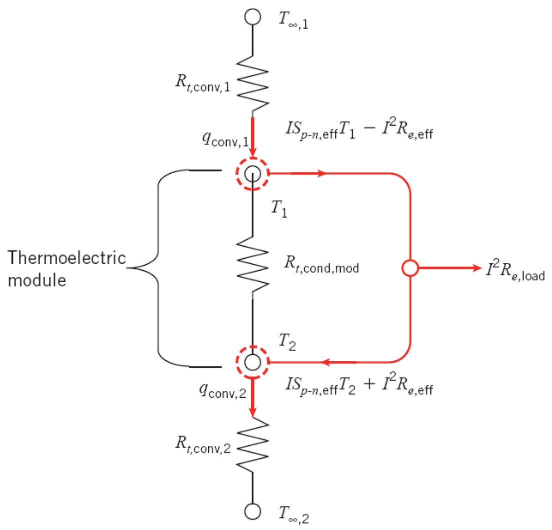


Figure 2: Model of thermal resistances adapted from Incropera (2011).

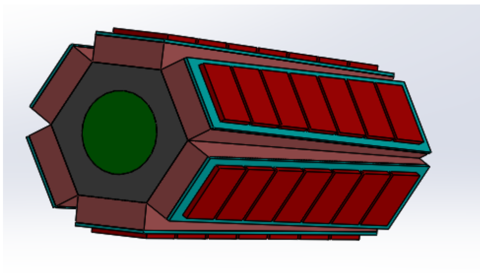


Figure 3: A suggested pickup hexagonal duct.

Table 1: Parameters set list

Parameter	Value
Total TEG amount	42
Structure form	Hexagonal
Maximum length	500mm
Model	TELBP1-12656-45
Dimension	56x56x5mm
Maximum operation temperature (T_m)	350°C

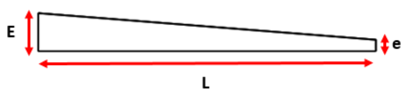


Figure 4: TEG Resistive Air Layer (RAL) with variable lengthwise section.

mized are the inlet thickness (E) and the outlet thickness (e), with constant dimension of the hexagon side, in such way the objective function described by expression (2) is satisfied.

$$f(x) = |T_m - T_e| + (t_i - t_o) \tag{2}$$

In (2), T_m being the standard temperature (operating limit of TEG), T_e the surface average temperature found at each iteration, t_i the inlet duct surface temperature and t_o the outlet duct surface temperature. The T_m temperature from the TEG analyzed was 350°C (Thermonamic, 2013).

The initial model was built in 3D and simulated according actual operating equipment conditions in a finite elements routine. The finite element model was validated from the data measured in the real equipment. The results are transmitted

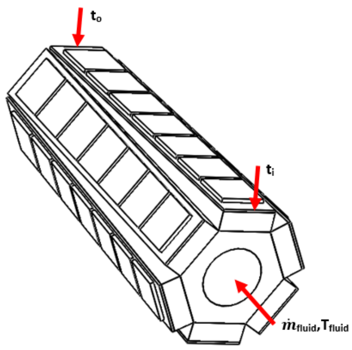


Figure 5: The t_i and t_o variables at cross-section duct.

to an optimization algorithm that checks the objective function (2) and returns, cyclically, new parameters to be analysed by the simulator for the convergence method. The optimization methodology ends when the error less than 1% is reached or when the algorithm reaches over 100 iterations.

The heuristic optimization method Brute-Force was chosen. With parameters based on random analysis, this algorithm, also known as generate and test, is a very general problem-solving technique that consists of systematically enumerating all possible candidates for the solution and checking whether each candidate satisfies the problem's statement. While a Brute-Force search is simple to implement, and will always find a solution if it exists, its cost is proportional to the number of candidate solutions, which in many practical problems tends to grow very quickly as the size of the problem increases. Therefore, Brute-Force search is typically used when the problem size is limited, or when there are problem-specific heuristics that can be used to reduce the set of candidate solutions to a manageable size or when the simplicity of implementation is more important than speed (Maringer, 2005). The flowchart methodological optimization in shown in Fig. 6.

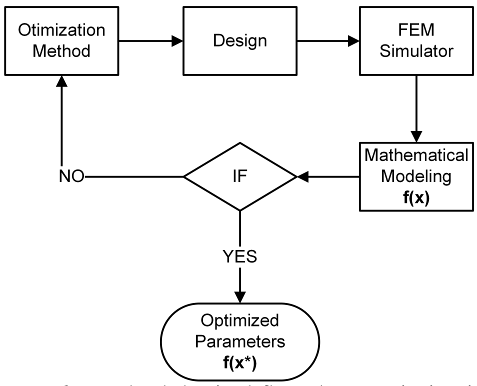


Figure 6: Methodological flowchart optimization.

3. RESULTS

The problem was modeling based its real boundary conditions using a finite element methodology.

The Reynolds number (R_e) is represent by the expression bellow:

$$R_e = \frac{\rho V D_h}{\mu} \tag{3}$$

In (3), ρ represents the fluid density, V fluid velocity, μ is fluid viscosity and D_h hydraulic diameter.

Thermodynamically, the exhaust gases were considered air. The gas volume flow rate is 0.415m^3/s (experimental data). If the average diameter is 50.8mm, it follows that the average speed is 204.75m/s. Interpolating the data density and viscosity of air at 500°C on expression (3), a high turbulent flow (Reynolds greater than 3000 (White, 2010)) was found; Re = 3,03x10^6.

The analysis was simulated using a live link between *Comsol Multiphysics* and *Matlab* on laminar flow condition (Reynolds less than 2400 (White, 2010)). Although it is a simpler solution, it would be the worst possible condition, once the turbulence increases the collision between the molecules of the system, consequently, increasing the heat transference to TEG, which would be beneficial. Also, a turbulent flow simulation needs unknown parameters as turbulent kinetic energy (k) and its dissipation (ϵ).

From the heat and mass differential transfer equations, its developed a steady state solution: Due to symmetry of the hexagonal geometry model, this one was splited in order to reduce computational efforts of differential solution equations by simulator. The main expression resolved by simulation are shown below.

$$\rho\left(u\cdot\nabla\right)=\nabla\cdot\left[-\rho I+\mu\left(\nabla u+\left(\nabla u\right)^{T}\right)-\frac{2}{3}\mu\left(\nabla u\right)I\right]+F \tag{4}$$

$$\nabla\cdot\left(\rho u\right)=0 \tag{5}$$

$$\rho C_{p}u\cdot\nabla T=\nabla\cdot\left(k\nabla T\right)+Q \tag{6}$$

In (4) and (5), ∇ represents a generic gradient, ρ fluid density, u fluid velocity, T temperature, μ is fluid viscosity and F a external fluid force. In expression (6), also C_p as specific heat capacity, k is a thermal conductivity and Q the exchanged heat.

Constraints of minimum thickness were established to limit the algorithm results to future possible physical construction. The convection heat exchange effects from external environment were considered from 400mm bounded region illustrated in Fig. 7.

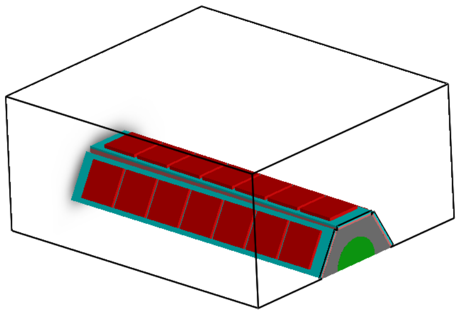
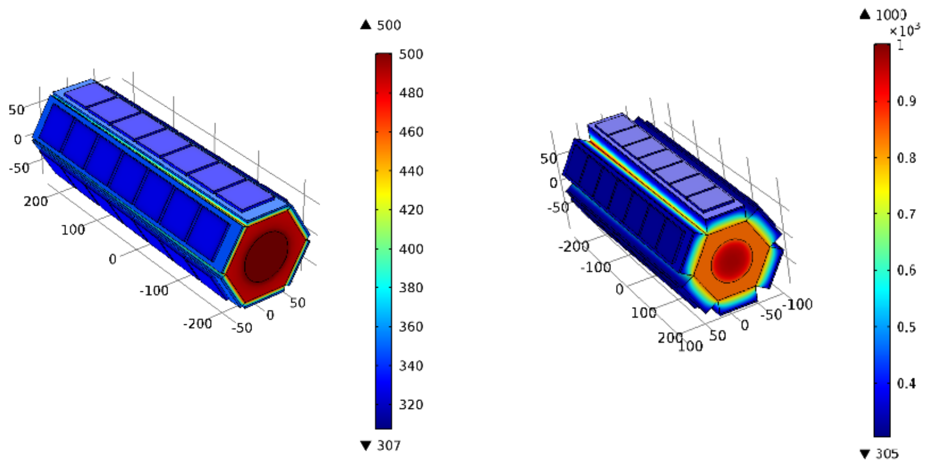


Figure 7: Convection heat exchange effects from external environment.

In order to increase the effectiveness of thermal resistivity thickness variation, several materials were simulated. Among them, aluminum, steel and copper. The steel model showed up the most cost-effective, with good temperature distribution and lower manufacturing costs.



(a) T_{fluid}=500°C. (b) T_{fluid}=1000°C.

Figure 8: Surface temperature distribution.

As the system temperature increases (transient regime), the air physical properties starts change. Air density decreases and its ability to store energy (ρ C_p), falls about 2.77 times between 400K and 1300K. Also, the air has its conduction coefficient increased 2.4 times for the same range, becoming less insulation.

For T_{fluid}=500°C, it was simulated 120 seconds in transient regime to analyze air properties variation and its interference in the results. Significant changes were not observed.

In Table 2, it was observed values obtained through simulation for various fluid temperatures. The heuristic method found E and e values for the lowest ΔT to the range 500°C to 1000°C.

Table 2: Optimized model results (ΔT).

$T_{fluid}(°C)$	$E(mm)$	$e(mm)$	$t_i(°C)$	$t_o(°C)$	$\Delta T(°C)$
500	7	3	346.65	346.57	0.08
550	10	5.5	343.75	344.04	0.29
600	12.5	7.5	346.65	347.25	0.60
650	15	10	346.00	346.22	0.22
700	18	12	344.93	345.89	0.96
750	20	15	343.74	343.49	0.25
800	24	18	346.84	347.28	0.44
850	25	19	344.45	344.69	0.24
900	27	21	346.67	346.71	0.04
950	29	23	348.26	348.16	0.10
1000	31.5	25.5	344.49	344.24	0.25

$$E(T) = -1.119e^{-5}T^2 + 6.169e^{-2}T - 19.79 \quad (7)$$

$$e(E) = E - 5.41 \quad (8)$$

In expression (7) and (8), T is fluid temperature (500-1000°C), E is inlet thickness and e is outlet thickness, both in mm.

In Fig. 9, from Table 2, a linear regression is shown.

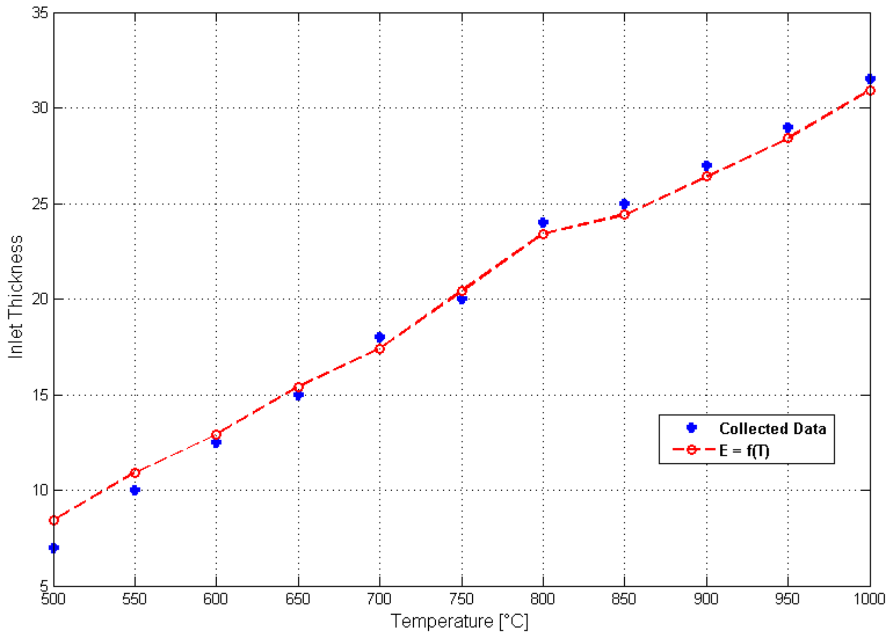


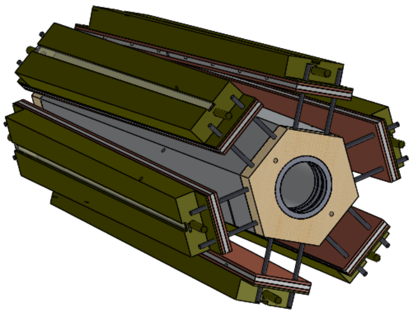
Figure 9: Inlet Thickness E (mm) x Temperature fluid (°C).

In Table 4 presents the results for two random values of T and its temperature variation between input and output to validate the curve. The results show minimal difference in the surface temperature between the inlet and outlet duct (null gradient).

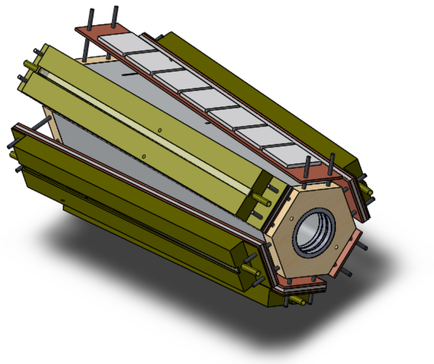
In Fig. 10(a), there is the inlet prototype view for the 1000°C source. A inclined plane in copper plate allows the resistive air layer equalize the surface temperature and to limit the temperature at 350°C (TEG operation limit).

Table 3: Curve validation.

$T_{fluid}(°C)$	$E(mm)$	$e(mm)$	$t_i(°C)$	$t_o(°C)$	$\Delta T(°C)$
630	14.6	9.2	342.08	341.28	0.80
925	27.3	22.3	350.35	349.59	0.76



(a) Inlet view.



(b) Outlet view.

Figure 10: Prototype plant.

In Fig. 10(b), is observed a heat exchanger in the cold part of the TEG by the outlet view. This heat exchanger has a water flow, automatically controlled by an on/off valve based on information of temperature sensors coupled to the cold side of TEG. The variation in temperature between the hot and cold part of TEG should remain as constant as possible according to the Datasheet information from electronic equipment.

From capturing duct optimizing manufactured, an electric generator coupled is proposed aiming to capture energy as shown in Fig. 11. With 42 TEG simulated in this preview work, and a 500°C of exhaust temperature from the electric generator used, is expected about 1kW of power electricity.

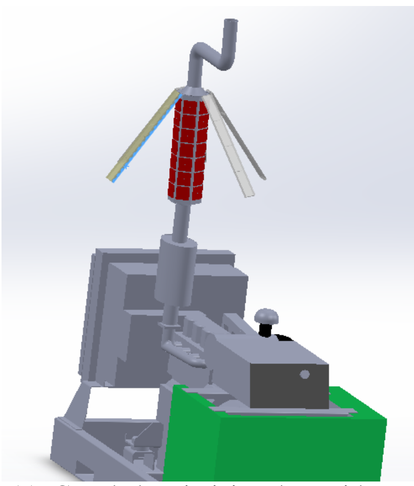


Figure 11: Coupled optimizing duct with generator.

4. CONCLUSION

Conversely, recent works found in the scientific community focus on obtaining new materials with higher Figures of Merit (Z), this is a pioneer work in search the increased energy conversion efficiency by optimizing the geometry of capturing duct.

The RAL presents good results in order to equalize the surface temperature. For all fluid temperature ranges, a zero gradient was found in the TEG contact surface. In addition, this paper presents an equation for obtaining the input and output thicknesses of RAL, describing a single constructive proposal.

For large sources of heat, this work allows a control system configuration with automatic variation of the air thickness (RAL).

A constant surface temperature in the capture duct allows the global energy maintenance, in exchange with the TEG, approximately constant. The lack of temperature variations between TEG allow them to work in an environment linearly, far away from mechanical failure and near to maximum electrical efficiency.

For next works it would be important a turbulent flow simulation (with the real Reynolds flow) in order to check for significant differences with the laminar regime solution on the final optimized design.

Differently from the existing jobs that have been connected to automotive industries, this work has diverse applications in hot waste sources energy, either exhaust vehicles or generators, either hot steam ducts released to atmosphere.

5. ACKNOWLEDGEMENTS

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