TherMaG: Engineering Design of Thermal-Magnetic Generator with Multidisciplinary Design Optimization

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Q1. Project selection

Pick a multidisciplinary system to analyze. Form a team of students who are interested in the same system. For the multidisciplinary design problem that your team has chosen, write a short (≈ 2 pages) project proposal. You should address the following:

Formal problem statement

On the existing trend of global warming and the catastrophes caused by the increasing temperature, there is no doubt that shifting and revolutionizing our energy form is becoming one of the most important goals for scientists, engineers, and the whole human race [IPCC Report]. Thus, with the effort and collaborations between governments, corporations, institutions, we are making great progress in advancing wind power [U.S. Energy Information (a)], electrochemical energies [Region, and Segment Forecasts], nuclear powers [World Nuclear Energy Assoc.], and many related clean energies for substitutes of traditional fossil fuels. However, a new form of clean energy, thermomagnetic power, was often neglected by the general public. In fact, adopting magnetic

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power as a new form of green energy is not a novel thing, and emerging and growing drastically in recent years, since it can also be employed as part of many renewable energies and functional equipment [MMTA, 2016]. For example, magnetic materials play a pivotal role in the efficient performance of devices in a wide range of applications such as electric power generation, transportation, air-conditioning, and telecommunications [Matizamhuka, 2018]. In general, the drive towards improving electricity transmission efficiency and the replacement of oil-based fuels by electric motors in transportation technologies has motivated researchers to focus on magnetic material technologies [Gutfleisch *et al.*, 2011]. Physics tells us that a change in a magnetic field generates electricity that can support our daily energy needs as a form of clean energy [U.S. Energy Information (b)]. In addition, a change of temperature field can cause the magnetic variation for specific materials under set conditions in solid-state physics [Kittel, 1986]. Hence, it is straightforward that a temperature change can generate magnetic change thus generate electric energy that meets our needs, which we may term as thermo-magnetic energy. To employ such kind of energy, a particular machine, named thermo-magnetic generator (TMG) is designed. Currently, the research and real-world applications are not widely touched by both academia and industry, compared with other forms of clean energy. Notwithstanding, the potential of TMG is huge since its magnetic are ubiquitous and the world demands clean energy strong.

The genius idea of the thermo-magnetic generator can be traced back to Nicola Tesla [Tesla, 1889]: Originally named PYROMAGNETO-ELECTRIC GENERATOR, whose idea employs two well-known laws: First, that electricity or electrical energy is developed in any conducting-body by subjecting such body to a varying magnetic influence. Second, the magnetic properties of iron or other magnetic substance may partially or entirely be destroyed or caused to disappear by raising it to a certain temperature, but it restored and caused to reappear by again lowering its temperature to a certain degree. The Tesla and Edison [Edison, 1892] patents originated more than 100 years ago formulated our basics to design such a machine.

In our design works, the TMG model was mainly adopted from Waske *et al.*'s work [2019], whose model was very similar to Tesla's original design yet more practical for to-

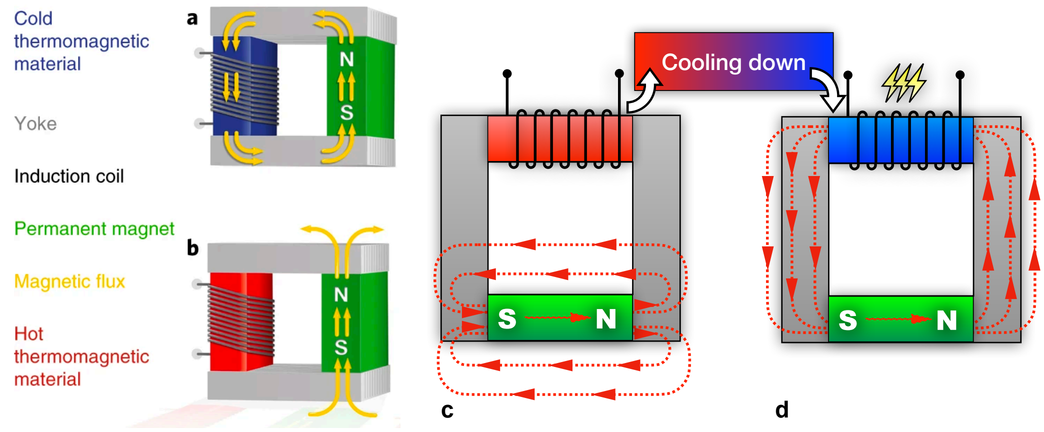

Figure 1: The schematic illustration of thermo-magnetic generator. Note that subfigures **a** and **b** are reproduced from Waske *et al.* [2019]. Subfigures **c** to **d** represents how the cooling down of the active magnetic materials generates electric power.

day's industrial applications, as illustrated in Figure 1 **a** and **b**. Our model is illustrated in Figure 1 **c** and **d**: a hollow squared-shape generator connects two pieces ferromagnetic materials - so-called *yoke* - without permanent magnetization on the two sides, rendered as different colors. The green material represents the permanent magnetic material, generating the magnetic field. The blue and red parts represent the active material when ”hot” and ”cold”, respectively, where we study whose behavior through changing the temperature thus causing its magnetic properties changing, according to Tesla [Tesla, 1889]. Heating up thus stops connection of magnetic field, while the magnetic field is trapped in the permanent materials, as in Figure 1 **a**. Cooling down causes ”activation” of active materials, thus making the magnetic field go through the whole generator, as in Figure 1 **b**. The variation process generates electricity.

In our project, we extend the system and also consider the mechanism by which the active material is heated up and cooled down. We propose a simple design scheme[1] where a flow channel is connected on top of the active material and is continuously supplying a flow of fluid through it. This fluid serves to enhance the heat-up and cool-down processes. These two processes, in conjunction, represent a thermal cycle, and we assume that the power output[2] of the device should simply scale with how long

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[1] which is definitely not the optimal one

[2] energy produced per time

this takes.[3] Note that the work of the pump as it pushes the fluid through has to be considered in the overall power output and efficiency of the system too. The work of the pump can be computed from the specified pressure difference and the fluid flow. We will divide this by an efficiency factor of the pump and subtract that from the power output, hence obtaining an *effective* power output. This of course, goes back into the efficiency of the system too.

As the active material is cooled down and heated up, the so-called *magnetic permeability* changes. This parameter defines the ability of a material to be magnetized in response to an external magnetic field. Through a complicated mechanism, this can cause the active material to either be *"guiding"* the magnetic field of the permanent magnet through it or not. As the magnetic field in the active material thus changes, a current can be induced in a coil wrapped around it. This current will, according to Faraday's law of electromagnetic induction, be proportional to the total magnetic flux going through the material, and we can thus try to optimize that.

We already have a lot of physical simplifications in mind. Not all of them are implemented in Q2. and Q3. of this assignment, but probably will be later. At this point, we are in principle still open to keeping some of them

Here, a simplified heating/cooling process will be considered, where we separately simulate the cooling/heating and the magnetic field/magnetization field. From the heating/cooling process, one can extract how long that takes; from the magnetic fields, we extract the difference between the total flux at maximum and minimum temperature of the active material. This temperature will be determined by looking at the so-called *Curie temperature* of the active material. Thus we define the duration of a heating/cooling cycle as the time it takes to get sufficiently above/below the Curie temperature in order for the permeability of the material to change a given amount[4]. The relation between the two can be found experimentally.Additionally, the temperature distribution will not be homogeneous, that is, the time it takes to heat up and cool down every infinitesimal point of the active material will not be the same. In this project we decide that every single point should be above or below a certain tempera-

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[3] We might, later on, decide that these two processes are roughly equal and only look at one of them.

[4] yet to be decided upon

ture in order for the material to be considered hot or cold [5]. The permeabilities of the active material at the hottest and coldest temperature are plugged into the magnetic module which will spit out the total magnetic flux at these extremes. The difference will be taken as proportional to total power output. We thus have to model outputs that will be proportional to the total power output, and we will make their product an objective of the optimization. In order to find the constant of proportionality, one would have to run an actual experiment, but for optimization in itself, it turns out not to be necessary. The temperatures around the Curie temperature to heat up and cool down around could definitely be made an object of optimization too, but we refrain from doing that since it would include a lot of physics that would take time away from the optimization itself.[6] A schematic diagram for our TMG systems are shown as in Figure 2. Note that essential definitions are made in this figure.

Here, we are curious how we can design the best TMG in this model considering as many modules involved with multidisciplinary optimization.

It is obvious that the TMG system involves complex disciplines, requires certain standards to optimize for a engineering solution, which can be tackled multidisciplinary optimization (MDO). In MDO, a problem involves multiple disciplines targeting specific objectives can be written in the following forms [Agte *et al.*, 2009]:

$$\begin{aligned} &\min f(\mathbf{x},\mathbf{p}) \\ \mathbf{x} = [x_1, ..., x_n]^T,\ &\mathbf{p} = [p_1, ..., p_m]^T \\ x_{i,LB} \le x_i \le x_{i,UB}, &\quad i = 1, 2, ..., n \\ \text{s.t.} \quad &\mathbf{g}(\mathbf{x},\mathbf{p}) < 0,\ \mathbf{h}(\mathbf{x},\mathbf{p}) = 0 \end{aligned}$$

where f is the objective function that we aims to maximize or minimize. $\mathbf{x}$ is a n-dimensional vector of design variables with lower and upper bounds, $\mathbf{p}$ is a vector of fixed parameters that influence the behavior of the system but cannot be freely chosen (material properties, operating conditions, ...), and $\mathbf{g}$ and $\mathbf{h}$ are inequality and equality constraints, respectively. These variables for our TMG will be presented in the following

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[5] This procedure is likely not optimal, but we can not optimize everything

[6] As of now, we are still listing choice of the active material as an input variable, but we are inclined to scratch that too and settle on Gadolinium, which is the conventional choice for a TMG.

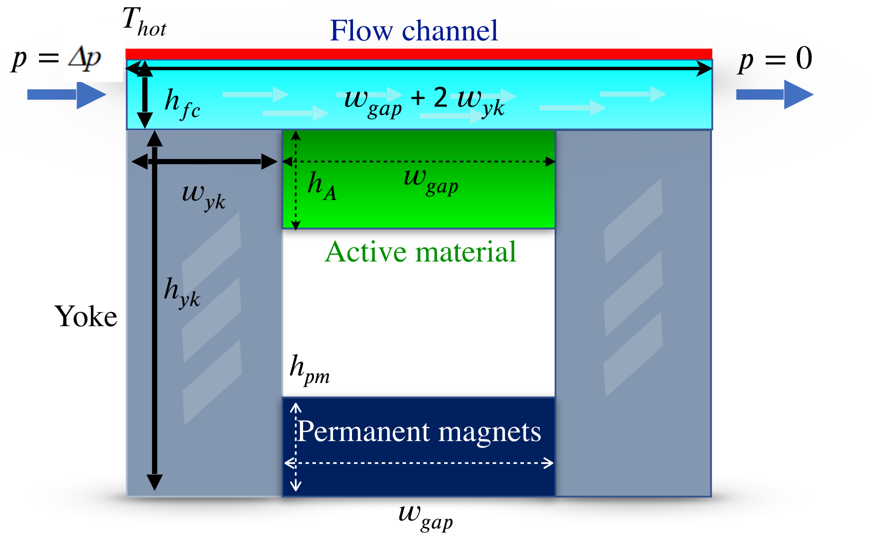

Figure 2: Our proposed design scheme. Notice in particular the flow channel in blue through which a fluid is pushed by a pump. This picture is to also serve as a reference to some of the variables/parameters mentioned later. In this picture, the green block is the active material; the dark blue is the permanent magnet; the grey ones are the yoke. The red bar on top signifies a *boundary condition on the temperature field.* During heating, it is "turned on", and is given by T_{hot} . During cooling it is "turned off" and is given by T_{cold}. The latter temperature also defines the boundary condition at all other outer boundaries of the configuration. Not that $p = 0$ is set as the reference pressure. We might as well have chosen $p = 1atm$, but in our simulation it makes no difference.

sections.

Technical estimation

For parameters, design variables and objective functions, we refer to table 1. Note that the geometric variables refer to all those shown in figure 2. We include also the dependent variables used as intermediate outputs of the model, which constitute inputs to other modules of it. If we were to explain everything, we would have to write twice as many pages, and have therefore described certain physical processes and variables/parameters a bit vaguely. We hope to make some of this more clear in the following assignments

Inequality constraints

(1) Total volume taken up by the device must fall below a certain threshold (it has to fit in a car. Maybe this can eventually be relaxed, so that the device only applies for large cars, or maybe for non-automobile applications, such as energy recouping at power plants) $(h_{yk} + h_{fc}) \cdot (2 \cdot w_{yk} + w_{\text{gap}}) \leq V_{\max}$

(2) We mention that the total weight of the device should perhaps not exceed a certain threshold either - one could imagine that the car would then get too heavy. This is closely coupled to the total volume however, since the densities of the raw material probably do not vary *too* much. Furthermore, in modern cars, the total volume will probably become a limiting factor long before total weight. In addition to the inequality constraint on volume, singular dimensions of the device should not exceed certain limits. For instance, even if the volume remains the same, could you imagine a device that is $10m$ long fit into a regular car? Probably not. Hence come the following inequality constraints,

(3) $(h_{yk} + h_{fc}) \leq L_{\max}$

(4) $(2 \cdot w_{yk} + w_{gap}) \leq L_{\max}$

We also say that we can not have material that *overlaps*. This creates the following constraint,

(5) $h_{yk} \geq h_{ac} + h_{pm}$ This says that the total height of the yoke has to be large enough to fit the combined heights of the active material and the permanent magnet. If this were not true, either the latter two would have to overlap, or we would need to change the fundamental design scheme.

Equality constraints

As of yet, we have not set any equality constraints. We do however "prophesize", that at some later stage we decide to turn the equality constaint, $(h_{yk} + h_{fc}) \cdot (2 \cdot w_{yk} + w_{\text{gap}}) \leq V_{\max}$ into an equality constraint, $(h_{yk} + h_{fc}) \cdot (2 \cdot w_{yk} + w_{\text{gap}}) = V_{\max}$, the reason being that more "room to work with" will *probably* be better. This assumption might turn out to be wrong though[7].

Bounds

We are formulating this problem in such a way that we do not have a lot of bounds. We have some constraints which could *sort of* be considered as bounds though, simply because they are very simple. These are the geometric constraints that the total "width" and "height" of the system can not exceed certain thresholds. If the width or height of all components except one becomes very small though, then we effectively have an upper bound on the remaining width or or heights.

We also have the bounds on every single continuous design variable - whether that be pump pressure or the width of the active material - that it can not be negative, which does not make physical sense.

For the discrete variables, *choice of active material* and *choice of intermediate fluid*, we have bounds in the sense that we only have a given selection to take from [8]. We have not yet settled on which fluids and solids to try out, but are very much aware that a long array of properties affiliated with the given substance will be relevant [9]

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[7] Perhaps because more pump would be required, for instance

[8] One might even say, "there are only that many elements in the periodic system"

[9] For the intermediate fluid for example, both the magnetic permeability and the mechanical properties will be important. More on that later.

Symbol	Nomenclature	Unit	Type
Geo	Geometric parameters	$[m]$	Design var.
ΔP	Forced Pressure Difference	$[Pa]$	Design var.
M_F	Choice of Intermediate Fluid	×	Design var.
M_A	Choice of Active Material	×	Design var.
P_O	Power Output	W]	Objective
η	Efficiency	[1]	Objective
$\mathcal{C}$	Cost	[$]	Objective
V	System Volume	$[m^3]$	Constraint
$\mathcal{C}$	Various geometric figures	[m]	Constraint
$\mathbb{C}$	Materials Cost	[$]	Parameter
η_P	Pump Efficiency	[1]	Parameter
μ	Active Material Permeability	$[H/s]$	Parameter
T_{cold}	Temp. of the environment (300 K)	$[K]$	Parameter
T_{hot}	Temp. Maintained by Heat Source	$[K]$	Parameter
v_{fluid}	Velocity of Fluid	$[m/s]$	Dependent var.
B_{field}	The Magnetic Field	$[T]$	Dependent var.
$\mathbb{B}_{ind}$	Mag. Field Induced by Coil Current	$[T]$	Dependent var.
M_{field}	Magnetization field	$[A/m]$	Dependent var.
T_{outlet}	Temp. at Flow Channel Outlet	$[K]$	Dependent var.
P_{pump}	Pump Power Consumption	$[W]$	Dependent var.
P_{elec}	System Electrical Power Output	$[W]$	Dependent var.

Table 1: The design table for the thermal-magnetic generator applied to MDO. Note that different types of variables are marked with different colors. Variables are abbreviated as var.; Temperatures are abbreviated as temp. to save spaces.

Goal

Designing a thermo-magnetic generator *used in automobiles*. For a given volume[10], we want to minimize the total cost of the material used[11], maximize the total *effective*[12] power output[13], and maximize the efficiency[14]. It is emphasized that a competition between the latter two runs very deep and that they could never both reach their respective optima jointly.

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[10] this volume being an estimate of what could fit in a car

[11] It turns out that the material used in this kind of system is very expensive and the main factor limiting the commercial potential

[12] as it was defined previously

[13] to be understood as the amount of power that is extracted from the system per *time*

[14] We will define to be the power output divided by the rate of energy loss as heat is ejected from a control volume around the whole system

Current status and outlook

We have clearly defined the problem and the design and variables and parameters. We are still debating how complicated a physical model we want to create. We have defined the system boundary and already realized that we can only hope to optimize the efficiency and power output times some constant, and will not produce the actual numbers, which would have to be calculated experimentally.

We have also come very far in terms of simulation of the magnetic field and the magnetization of the different materials. A numerical model has been created, which can calculate the total flux through the coil at a given magnetic permeability of the active material. Much thought has also been given to the subject of fluid dynamics, although the convection of heat is still a matter to be researched. Another major difficulty will probably be the extraction of different simulation results from different COMSOL[15] models so that they can be analyzed in conjunction. Especially when it comes to evaluating that the temperature at no place in the model exceeds or falls below a certain threshold, there might be trouble ahead.

By the end of the semester, we hope to have spent most of our time on the actual optimization, and not the physics. We hope that we will have created a model that is closely enough related to reality so as to be a meaningful subject of optimization. Conducting a successful optimization of whatever design/function space we end up with, is however our main aim.

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[15] or maybe some other simulation tool

Inputs		*Geo*				*Geo*						
		M_A			Geo	ΔP					M_A	
	Geo	M_F	*Geo*	*Geo*	ΔP	M_F	*Geo*			*Geo*	*Geo*	
	Heat Transfer & Local Temp.	T_{fluid}							T_{outlet}			
		Permeability Field	μ									
			Magnetic Configuration	M_{field}								
			B_{field}	**Magnetic Field**			Φ					
					Pump Characterization			P_{pump}				
	v_{fluid}					**Navier-Stokes Computation**			v_{fluid}			
				$\mathbb{B}_{ind}$	v_{fluid}		**Coil Current**	P_{elec}				
								Power	P_{out}			P_{out}
									Efficiency			η
										Volume		V
											Cost	$\mathscr{C}$
												Outputs

Figure 3: The N^2 diagram for the TMG system.

Q2. Coupling and N^2 Diagram

For the problem that you have chosen, identify the modules (see guidelines from Lecture 3), and identify the inputs and outputs for each module. For simplicity, limit the number of modules to about seven, plus or minus two (7+/-2) at this point.

For the original and rearranged N^2 diagram please refer to Figure 3 and Figure 4. As is clearly indicated by the two diagrams, huge progress was made as we went from the initial random order to the rearranged diagram.

Q3. Block diagram

Sketch a block diagram that shows how the modules from your previous answer to **(part b, Q2)** work together and how you would wrap a trade space exploration tool or optimizer around your simulation model. You don't actually have to implement this (yet). That will happen in assignment A2.

Input	ΔP			M_F								
	M_F		Geo	M_A							M_A	
	Geo	M_F	ΔP	Geo	Geo	Geo	Geo			Geo	Geo	
	Navier-Stokes Computation	v_{fluid}	v_{fluid}						v_{fluid}			
		Heat Transfer & Local Temp.		T_{solid}					T_{outlet}			
			Pump Characterization					P_{pump}				
				Permeability Field	μ							
					Magnetic Configuration	M_{field}						
					B_{field}	**Magnetic Field**	Φ					
						$\mathbb{B}_{ind}$	**Coil Current**	P_{elec}				
								Power	P_{out}			P_{out}
									Efficiency			η
										Volume		V
											Cost	$\mathscr{C}$
												Outputs

Figure 4: Rearranged N^2 diagram for the TMG system. You will notice the green box drawn around the "magnetic part", that will be done in one simulation, and the blue box around the "convective heat transfer part, that will be done in another.

For the block diagram please refer to Figure 5. Here, parameters are in yellow, design variables in red, objective functions in blue, and computational modules in green. Note that the *Number of turns* is very much in parenthesis. In this block diagram we have included *nearly* all the of the relevant physical processes. We show this and emphasize that cuts will be made and the whole analysis simplified. As this is done, *Number of turns* will overwhelmingly likely become irrelevant. In purple we have constraints, which are all geometric and included in *system volume*, although some of them are in fact one-dimensional and not two-dimensional.

As for the trade exploration, we have not settled on any method yet, but we think it might be useful try out certain fixed combinations of design variables in the "blue" and "green" modules[16], *only after having optimized design variables of these modules internally*.

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[16] as indicated on the N^2 diagram

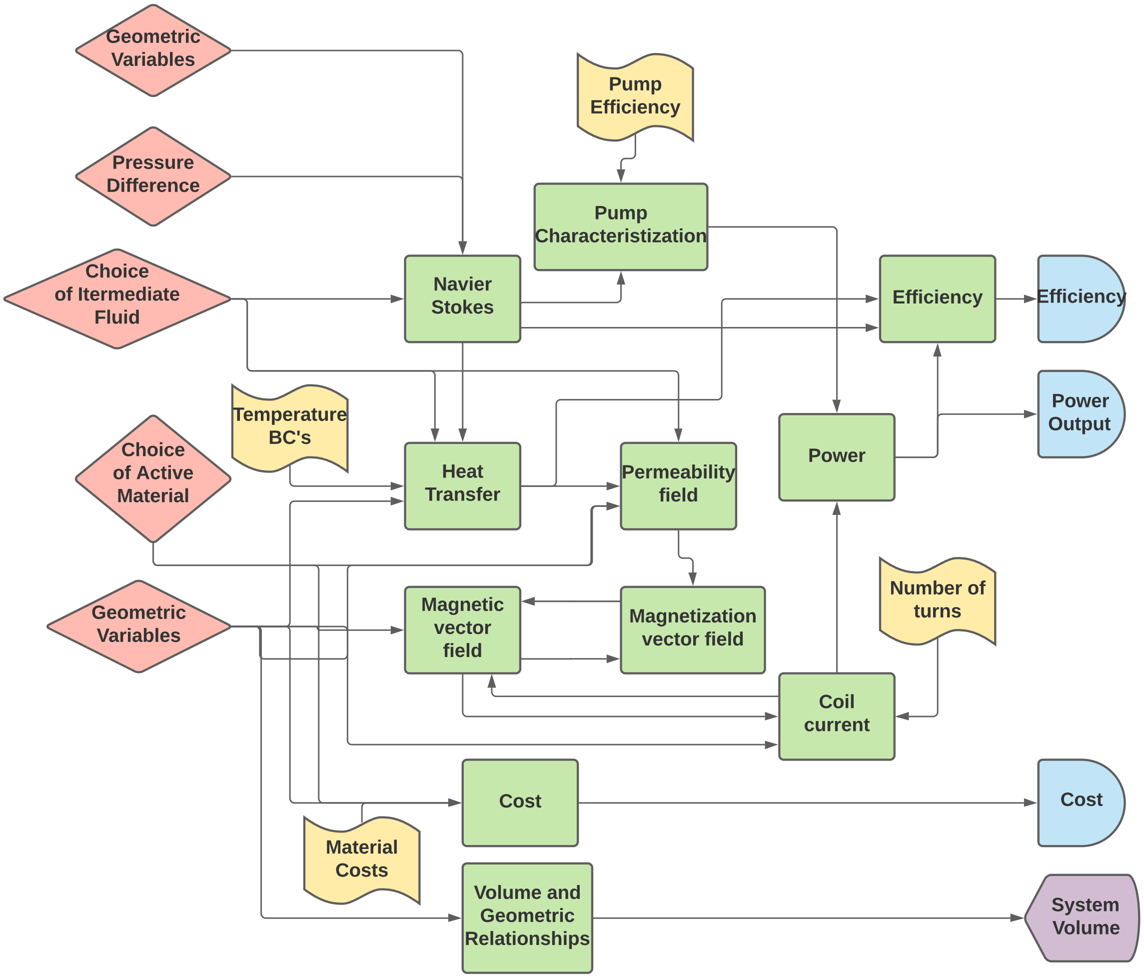

Figure 5: The block diagram for the TMG system.

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