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Future Structural Materials of High Speed Generators Used in Supercritical CO_2 Based Power Plant Applications

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Abstract

The aim of this paper is to present the applicability of one of the promising achievements in the fields of materials science and mechanical engineering, which provides a solution to one of the problems of the new generation power plants. One promising area of research aimed at increasing the efficiency of electricity generation is discussed in this article on the characteristics of super-critical carbon dioxide power plant cycles and the properties of high-speed generators that can be used in such power plants. The applicability of amorphous materials in the construction of high-speed electrical machines can solve the efficiency problem of such machines, enabling its use in new generation power plants.

Keywords: *supercritical CO_2, electromagnetic machine, amorphous material.*

1. Introduction

The world's demand for electricity is constantly increasing [1], The rapid spread of industrial automation and electromobility requires the development of an electrical grid. In order to do development near moderate emission of harmful substances, attention must also be paid to increasing the efficiency of power plants in addition to the development of power plant capacity. Today's steam-powered Rankine cycle power plants have more than 100 years of history, but the efficiency of modern power plants is just over 30 % [2]. Further increase in efficiency is only possible with the introduction of new technologies. One promising technology is the use of supercritical carbon dioxide (sCO2) as a working fluid in the power cycle. The sCO2 working fluid promises an excellent opportunity to achieve higher thermodynamic efficiency, up to 47 %, mostly using the Brayton thermodynamic cycle [3]. Due to the properties of sCO2, it requires the development of revolutionary power plant equipment, for example, the sCO2 turbine provides the same capacity as a steam turbine with significantly smaller geometry. As a result, the turbine speed is notably higher, whereas a conventional generator would be driven through a reduction gearbox. In the case of power plant performance, the efficiency of the transmission impairs the overall efficiency of the energy conversion chain, although the installation and operating costs are also significant. A better solution is to use a high-speed generator, which can be directly driven by the high-speed turbine. With the help of modern power electronic devices, it is possible to generate either 50 Hz or DC voltage from the voltage produced by the generator at a higher frequency than the mains frequency with good efficiency. To bridge long distances, several direct current electric power transmission lines (HVDC) have been built in recent decades. These have the advantage of higher energy transfer, lower losses (no skin effect, interference, etc.) and no need for synchronization, so the distance is not limited by stability problems [4].

The stator of high-speed generators is made of Fe-Si soft magnetic materials, which have unfavourable high-frequency magnetic properties. Due to this, the electromagnetic machine operated at a higher frequency (speed) dissipates more heat due to the increased iron loss; therefore, its efficiency is lower. Materials science research shows [5], that iron-based soft magnetic materials with amorphous structure have significantly better high-frequency magnetic properties, so that they can be used to build high-efficiency electromagnetic machines with increased efficiency. Generators built using amorphous materials are able to convert mechanical energy from a high-speed sCO2 turbine into electricity with good efficiency, thus contributing to the industrial application of sCO2 technology.

2. Properties of supercritical carbon dioxide power plants

A thermal cycle using supercritical carbon dioxide (sCO2) can help combat climate change and its impact, as the working medium results in higher thermal efficiency at lower investment costs than state-of-the-art steam (Rankine) power cycles. Power plants using the sCO2 cycle process are compact, it is projected to require a tenth of the space [6]. The unique characteristics of the sCO2 working fluid are attracting widespread interest, many research groups are dealing with the applications of the technology [7].

If carbon dioxide is kept above its critical temperature and pressure, it enters a supercritical state. In this state, it is characterized by a density close to liquids and a viscosity close to gases, which parameters can also be dramatically modified by a small change in temperature or pressure, so that sCO2 is a highly efficient working fluid for power cycle. The phase diagram of CO_2 is shown in **Figure 1**.

The fields of applications of the sCO2 cycle, which promise to be extremely wide, can be used more efficiently than conventional steam cycles in converting high-temperature thermal energy into electricity.

It can be used, for example, for the development of energy storage systems [8], for the construction of a concentrated solar power plant [9], novel hybrid geo-solar thermal power plant [21], or for waste heat recovery equipment [10].

A further application area is the use in 4th generation nuclear power plants as a working fluid for the power cycle. It can be used to build smaller, more efficient nuclear power plants, which is a significant advantage for military nuclear-powered ships and submarines, for instance. The efficiency of such power plants is calculated to reach 47 % [3], and a very significant natural convection flow of sCO2 is also beneficial from a safety point of view [11]. Several studies have focused on the selection of a high-efficiency power cycle that meets the requirements of 4th generation nuclear power plants, and research has shown that the sCO2 working medium is the best choice in terms of both feasibility and cost, as well as efficiency [12].

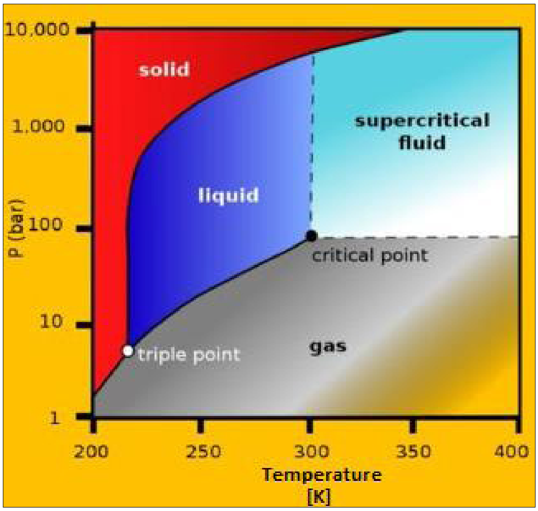

Figure 1. *Phase diagram of CO_2.* [13]

The Brayton power cycle is the most suitable cycle for the sCO2 working fluid. Due to the low pressure ratio (2-3), arrangements with heat exchangers, multistage compressors and intercoolers in several arrangements are investigated by simulations and experiments. **Figure 2.** shows the arrangement of a heat exchanger Brayton cycle with two compressors, which was also investigated in [15] by measurement and simulation.

Using sCO2, the size of power plant equipment is significantly reduced [16], due to the use of high-density working fluid. The sizes of power cycle components are about one-fifth to one-tenth compared to steam-powered plants; **Figure 3.** shows a proportional comparison of 10 MW sCO2 and a steam turbine.

Such a reduction in size brings a number of technical problems into account. A group of problems is due to the higher speed of the turbine, which raises the issue of balance and sealing. The seal of the high-speed turbine shaft must seal a large pressure difference at high surface speed, for which non-contact seals (e.g. dry gas seal [17]) are the most suitable.

The use of sCO2 has the following advantages and disadvantages [19]:

- Simpler and more compact design;
- Higher efficiency;
- Potentially lower investment cost;
- Large heat exchanger surface required;

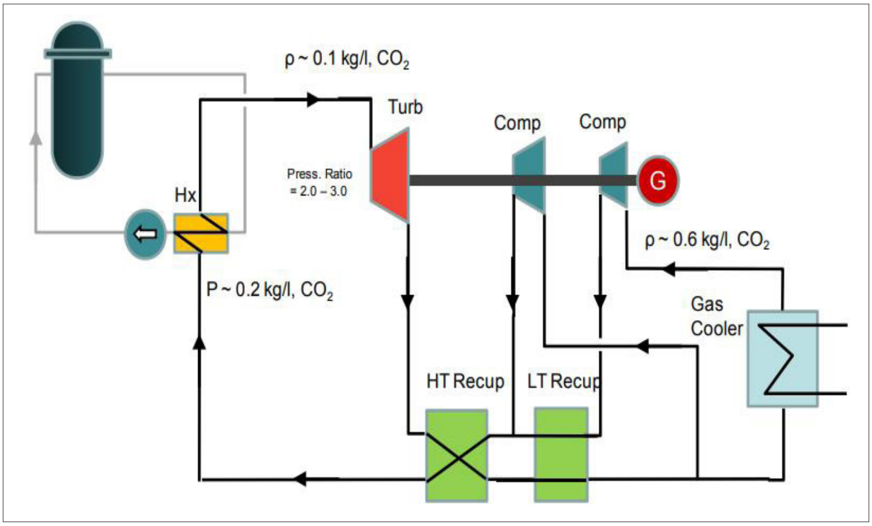

Figure 2. *Recompression Brayton cycle with sCO2 working fluid for high temperature nuclear power plants.* **[14]**

- Thick-walled pipes and equipment due to high pressure;
- Turbine and compressor construction difficulties, new types of sealing solutions are required;
- Higher operating costs.

3. Losses of high-speed electromagnetic machines

For electromagnetic machines, like generators and electric motors, the increase in power and speed may be limited by mechanical strength limitations, and a significant increase in electric and magnetic losses.

Increasing losses mean increasing heat generation and the requirement for more intensive, more efficient, complex and expensive cooling systems.

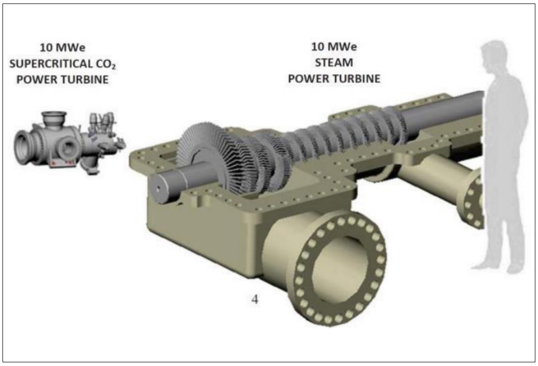

Figure 3. *Comparison of the size of a 10 MWe steam turbine and a sCO2 turbine.* **[18]**

Iron loss is an energy loss associated with heat production during alternating magnetization, which increases with AC frequency. According to their physical nature, iron loss can be broken down into three losses:

- hysteresis loss
- eddy current loss, which is negligible in the case of ferrites compared to other losses',
- loss due to domain wall movement.

A typical B-H curve of Fe-Si soft magnetic material can be seen in **Figure 4. [20]**.

After magnetization of the ferromagnetic materials by excitation, the remnant induction (B_R) that appears upon the termination of excitation can only be eliminated by excitation in the opposite direction. The point of intersection of the curve B-H with the horizontal axis is the coercive force (H_K), which is the value of the magnetic field

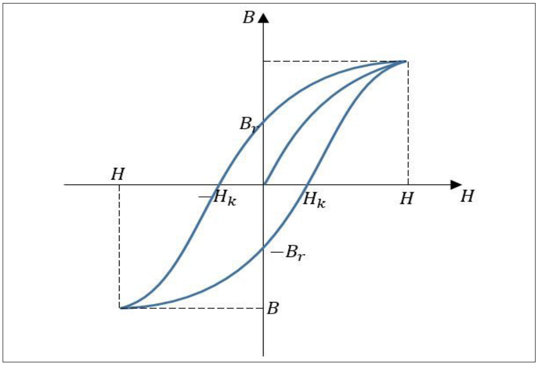

Figure 4. *B-H curve of ferromagnetic materials.*

required to eliminate the remanence induction of the magnet.

In the case of an iron core that is placed in an alternating magnetic field, the change in induction does not take place without loss, the amount of energy required for magnetization is proportional to the area enclosed by the hysteresis curve (**Figure 4**). In the case of electromagnetic machines, the number of magnetizations in a certain time is proportional to the speed of the machine, so the resulting power loss is also proportional to it. The magnitude of the hysteresis loss is directly correlated with frequency *(1)*.

$$P_{hiszt} = k_{hiszt} \cdot \Psi^2 \cdot f \,, \qquad (1)$$

where k_{hiszt} coefficient highly depends on the geometry of the iron core.

An effective reduction of the hysteresis loss is possible by reducing the value of the coercive force, which is primarily a function of the material characteristic. In electromagnetic machines, therefore, soft magnetic materials are widely used due to their lower coercive force values and lower hysteresis losses.

A loss is caused also by the eddy current induced in the iron core due to variable flux. The magnitude of the loss caused by the resulting eddy current is inversely proportional to the resistance of the iron core **[20]**.

The power loss of eddy current increases with the square of the frequency and flux *(2)*

$$P_{örv} = k_{örv} \cdot \Psi^2 \cdot f^2 \cdot \qquad (2)$$

A proven method of reducing eddy current loss is to assemble the stator or core from electrically insulated thin sheets.

In the presence of a magnetic field, the boundaries of the domains in ferromagnetic materials move, which is called domain motion. Displacement consists of translational motion and, near the saturation limit, the turning of moments toward the outer space. As a result of this movement, the size of some domains increases, some decrease. In an alternating magnetic field, the change of these domains happens periodically, which results in a loss of energy and consequent heating. The power loss due to the movement of the domain wall is linearly proportional to the frequency.

In the case of high-speed electric motors and generators, the rate of iron loss due to high frequency starts to increase dramatically, as shown in **Table 1. [5]**.

Table 1. *Iron loss of soft magnetic materials NO10 and NO12.* **[5]**

Class	Thickness (mm)	Iron loss at 400 Hz (W/kg)	Iron loss at 2500 Hz (W/kg)
N010	0.10	13.0	135
N012	0.12	13.5	132

The reason for the significant increase can be seen in **Figure 5.** The change in the shape of the BH curve due to the increase in frequency can be significant, which is due to the fact that the change in the magnetic orientation of the domains cannot follow the rate of magnetic field change. The coercive force of the material increases significantly **[5]**.

Despite the efforts of soft magnetic plate manufacturers, the high-frequency limit in usability of crystalline magnetic materials has reached its limit.

The need to increase efficiency e.g. in the case of electric motors, it is unquestionable due to the increasingly stringent regulations.

In the case of electromagnetic machines, one of the promising possibilities for increasing the degree of efficiency is the use of iron-based amorphous alloys. In these materials, a significant decrease in coercive force is observed due to the change in the inverse relationship between grain size and coercive force. The coercive force showing a decreasing trend as a function of particle size, resulting in a significant reduction in iron loss.

In the case of electromagnetic machines, the so-called loss power density is obtained as the quotient of the electrical loss power and the motor volume. For machines with air cooling, this limit is approximately 300 W/litre.

Figure 6. illustrates the power density of a HITPERM nanocrystalline alloy (blue dotted line) as a function of frequency compared to similar properties of other widely used crystalline materials. It can be seen that using HITPERM nanocrystalline materials, the same loss occurs at a frequency of 1 order of magnitude.

In addition to the lower coercive strength of HITPERM alloys, another advantage is the manufacturability of 0.005-0.050 mm thick sheets, which causes a further reduction in iron loss through a reduction of eddy current **[20]**.

The use of FINEMET alloy is also promising in these applications, with the help of several heat treatment methods to further improve the properties **[23]**.

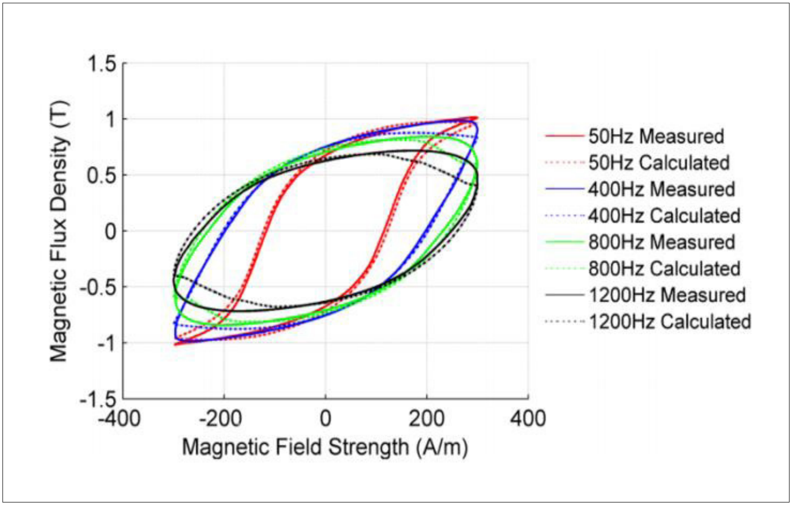

Figure 5. *Distortion of B-H curve due to high frequency changing of magnetic field.* **[22]**

The use of nanocrystalline materials may be limited by the fact that the improvement of magnetic properties is accompanied by a deterioration of the mechanical properties, which means that the material becomes brittle. This places a special limit on the mechanical manufacturability of such thin sheets, and the use of new manufacturing processes becomes necessary, e.g. the use of laser cutting technology, which has being widely researched **[5]** **[24]**.

4. Summary and conclusions

Due to the characteristics of supercritical carbon dioxide (sCO2) power cycles, it is necessary to use a small but high speed turbine, which makes it necessary to solve complex technical problems. The speed of the high-speed shaft of the turbine must be reduced to convert the mechanical energy into electrical energy with a conventional synchronous generator. In addition to power plant capacities (100 MW), the use of such speed deceleration gears is a rather inefficient, and involves high investment and high operating cost. In order to improve the efficiency of such applications, it is necessary to introduce other new technologies in order to eliminate the use of speed deceleration gearbox.

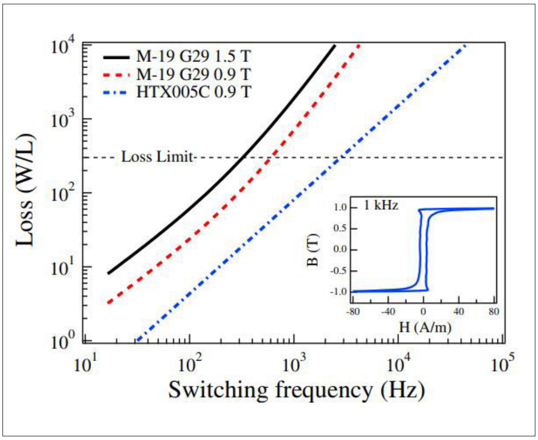

Figure 6. *Example of iron loss dependency to frequency* **[20]**

The efficiency of electromagnetic machines decreases with increasing speed. This can be explained, among other things, by the increase in iron loss, the coercive force in soft magnetic materials increases with the frequency, and the B-H curve becomes wider. Depending on the material, this causes significant loss in efficiency above a certain frequency, with a significant heating of the electromagnetic machine. Reducing the iron loss at high speed (frequency) allows the reducing gearbox between the turbine and the generator to be omitted in the sCO2 application, so the turbine can drive the generator directly. With this direct drive, the highest energy conversion efficiency can be achieved, so energy efficiency can be increased and the environmental load can be reduced.

Among the soft magnetic materials, the amorphous metallic glasses have the lowest coercive force in high-frequency magnetic fields, so their application has yielded great results in reducing the iron losses of high-speed E-motors and generators. The use of such amorphous materials in the construction of an electromagnetic machine requires the development of new types of manufacturing processes and material testing technologies due to the characteristics of the raw material. Summarizing the results of several domestic and international researches, it can be seen that it is possible to build a high-speed electrical machine with increased efficiency using amorphous materials.

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