Comparative analysis of linear motor geometries for Stirling coolers

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Abstract. Compared to rotary motor driven Stirling coolers, linear motor coolers are characterized by small volume and long life, making them more suitable for space and military applications. The motor design and operational characteristics have a direct effect on the operation of the cooler. In this perspective, ample scope exists in understanding the behavioural description of linear motor systems. In the present work, the authors compare and analyze different moving magnet linear motor geometries to finalize the most favourable one for Stirling coolers. The required axial force in the linear motors is generated by the interaction of magnetic fields of a current carrying coil and that of a permanent magnet. The compact size, commercial availability of permanent magnets and low weight requirement of the system are quite a few constraints for the design. The finite element analysis performed using Maxwell software serves as the basic tool to analyze the magnet movement, flux distribution in the air gap and the magnetic saturation levels on the core. A number of material combinations are investigated for core before finalizing the design. The effect of varying the core geometry on the flux produced in the air gap is also analyzed. The electromagnetic analysis of the motor indicates that the permanent magnet height ought to be taken in such a way that it is under the influence of electromagnetic field of current carrying coil as well as the outer core in the balanced position. This is necessary so that sufficient amount of thrust force is developed by efficient utilisation of the air gap flux density. Also, the outer core ends need to be designed to facilitate enough room for the magnet movement under the operating conditions.

1. Introduction

The Stirling cycle coolers were first introduced to the commercial market in the 1950s as small single cylinder air liquefier and a cryocooler for infrared sensors to about 80 K [1]. A distinctive feature of Stirling coolers is that the integration of the processes of compression and expansion of the working medium, heat exchange between forward and reverse flows, and external heat exchange with the object being cooled and with the surroundings of the same device. These characteristics make them compact and thermodynamically very efficient. In the recent years, the trend is to use the linear motor to provide motion to the compressor piston. Linear motors can have high precision and also long maintenance-free operation. Looking at the various motor types, we see that a linear motor directly converts electrical energy into linear mechanical force and is directly coupled to the load. Deployment of the unique linear drive mechanism in Stirling cryocooler makes them most attractive for space and military applications because of high reliability over extended periods.

Linear motors generate force in the direction of travel of the piston. They are capable of extremely high speeds, quick acceleration and accurate positioning. The stroke of the piston is easily controllable by regulating the input voltage. In the linear motor category, there can be moving iron, moving coil and moving magnet types. The moving iron motor has become obsolete because it has been found that the moving iron was rotationally unstable in its air gap. The analysis on moving coil type shows that the magnet volume required to generate the field of a moving coil machine is many times greater than that of a moving magnet machine of the same output and efficiency [2].

Also moving coil motors are haunted by its inherent life-limiting problems such as rupture of lead wires and out-gassing by the coil lamination. Compared to moving coil linear motor, moving magnet type offers numerous advantages such as less magnet volume and good thermal dissipation characteristic of the coil windings. In this context, splendid of scope exists for understanding new trade-offs in moving magnet type motor. Most of the research carried out were of specific in nature and used axially energized magnets. The axially energized magnet concept is relatively simple and easy to fabricate compared to radially energized one. The disadvantage of the former is that the magnet weight becomes more and space requirement is large. On the other hand, radially energized magnet rings are difficult to fabricate, especially magnetization and finishing. The understanding and application of the model are not simple when compared to the axial one. The coil winding, relative position of magnet ring, core geometry and air gap play a major role in deciding the force generated in the axial direction by keeping the losses to a minimum. This paper presents a comparative study of various possible configurations of radially energized moving magnet linear motor based on geometrical and electromagnetic parameters. Available permanent magnet (PM) materials are studied and the linear motor configurations are analysed in detail.

2. Linear motor geometrical configurations

A linear motor is conceptually a rotary motor whose stator core has been cut and unrolled. The circular stator becomes a linear stator, defining a single-sided linear induction motor. Cutting and unrolling the stator leads to many other possible linear motor configurations. To optimize performance, the gap between the magnet and core must be very small compared to the magnet thickness. Unlike rotary motors, the linear motor has a beginning and an end to its travel. The basic motor theory for each type of motor applies equally to both linear and rotary motors.

The linear motors work on the Lorentz force principle. According to this principle, if a current-carrying conductor (or coil) is placed in a magnetic field, a force (F) will act on it. The magnitude of this force is determined by the magnetic flux density (B), current (i) and orientation of the field and current vector. In simple words, a current carrying conductor placed in a magnetic field will have a force exerted upon it [3]. This force is proportional to the direction and magnitude of the current and the flux density field. Since the permanent magnet flux density field is fixed, the direction of the linear displacement depends on the polarity of the input current. The force is generated by the interaction between the magnetic field created by the permanent magnet or dc windings and the current carrying conductor. Every magnet structure consists of a permanent magnet and a steel return path. The heat transfer from the coil winding to the stator (outer core) is efficient due to the absence of insulating air gap between them, compared to moving coil design. Also, the mass of the coil is not at all a matter of concern in the moving magnet design.

Figure 1 shows the half cross-sectional view of a typical moving magnet linear motor. When AC is provided to the coil winding, the alternating electromagnetic field that the current produced interacts with the constant magnetic field produced by the magnet. This produces a force in the axial direction, which drives the mover (the coil or the magnet depending on the type of motor) back and forth continuously, together with the connecting part, and moves the piston. The radial forces in the proposed motor would result from Maxwell force and the axial force is generated by the current in the coil due to Lorentz force.
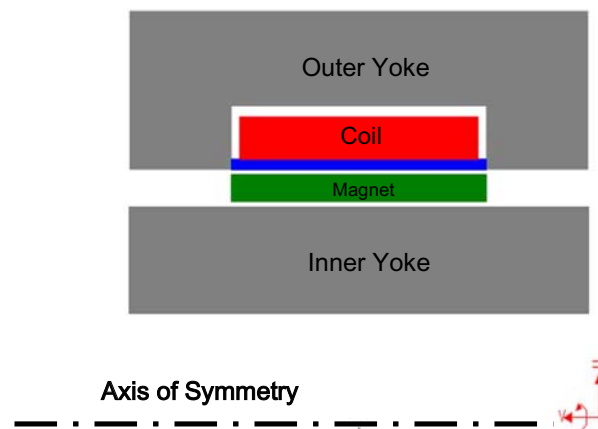
Figure 1. Typical moving magnet linear motor geometry.

The PM can be non-rare earth magnets or rare earth magnets. Although non-rare earth magnets are used in the majority of the applications due to their economic cost, rare earth permanent magnets have many distinguishing characteristics, such as a large maximum energy product, (one performance index for PMs). Dozens of magnetic materials which contain rare earth have been developed recently. Two major families of rare earth permanent magnets, samarium cobalt (Sm-Co) magnets and neodymium iron boron (Nd-Fe-B) magnets, have been widely used in a variety of applications. Each family has its own advantages and disadvantages [4]. Nd-Fe-B magnets have a higher Maximum Energy Product, $(BH)_{max}$ than Sm-Co magnets. $(BH)_{max}$ of Nd-Fe-B can easily reach 30 MGOe and even goes up to 48 MGOe. Nd-Fe-B magnets can replace Sm-Co magnets in most cases, especially where operating temperature is less than 80°C. The Nd-Fe-B magnets, introduced in 1985, have enabled the transformation of the moving magnet linear motor from a laboratory status to commercially viable one. Their high energy product $(BH)_{max}$ and stiff intrinsic coercivity (H_{ci}) allow high magnetic flux densities to be pushed across the large air gaps inherent in most linear motor designs while withstanding the demagnetizing fields generated by these linear motors' coil windings. As discussed earlier, compared to axially energized magnets, the radial aligning field required when pressing a Nd-Fe-B ring is extremely difficult to generate.

Moving magnet linear motor can be categorized into two in terms of stator core geometry: one with flat teeth and another with extended teeth. Figure 1 shows the motor with flat teeth, in which the outer core has a flat bottom with an axial height equal throughout the radial direction on either end. Figure 2 represents the motor with extended teeth, in which there are projections outward in the axial direction resembling teeth on either end.

Figure 2. Linear motor with extended teeth.

The analysis performed using finite element analysis (FEA) software Maxwell shows that in the motor with extended teeth, the inner core is subjected to magnetic saturation more easily when compared to the one without teeth. This would result in increased core losses, subsequently. In order to avoid the saturation of the core, the core diameter needs to be increased. But, this will eventually

result in the increased diameter of the outer core and increased weight of the system and hence in a dynamic instability of the entire system. Since the overall diameter and weight of the motor needs to be restricted to develop a compact and lightweight cooler, the motor with flat teeth is considered for further analysis. Various configurations under that category are analyzed in detail as discussed below.

3. Results and Discussion

The flux density in the air gap, generated by the combined effects of the magnetizing field of PM and of current carrying coil, influences the back EMF generated by the magnet. The force generated is directly dependent on the air gap flux density [5,6]. It has been observed from the finite element analysis that the material of the PM and core also influences this thrust force (Lorentz force) generated.

(a) PM under coil   (b) PM at middle of the yoke teeth

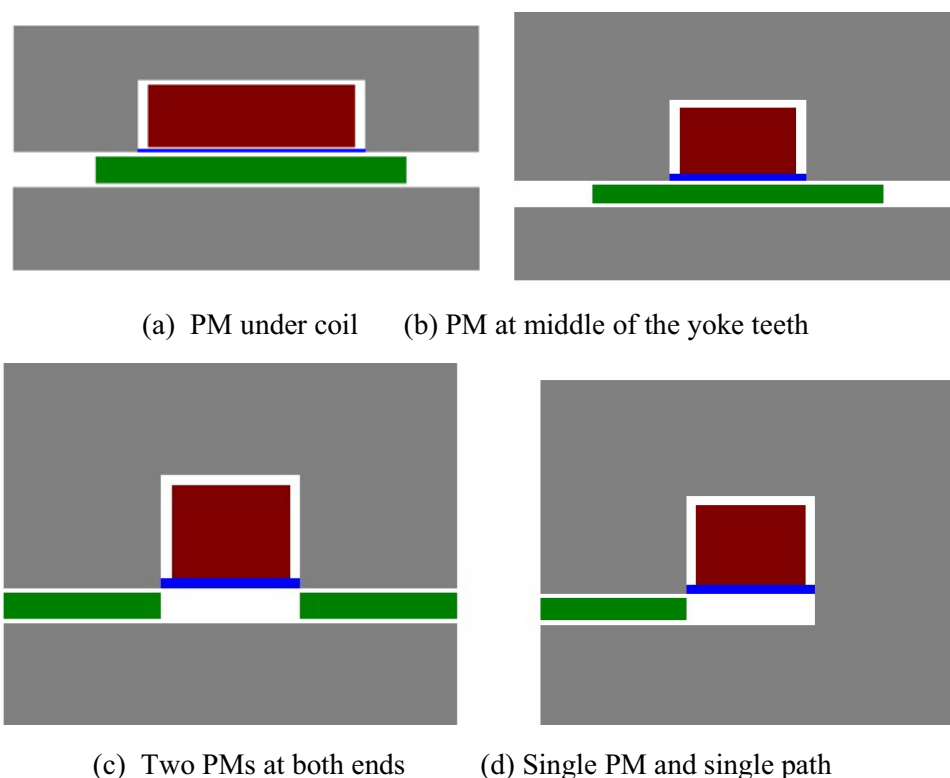(c) Two PMs at both ends   (d) Single PM and single path

Figure 3. Linear motor geometrical configurations.

The magnetic field distribution at the zero displacement position (when the magnet is in the centre of the motor geometry) for the motor with extended teeth and the one with flat teeth is shown in figure 4. The magnetic field in the air gap is the result of combined effect of the permanent magnet and the current carrying coil [7]. Usually, the magnet field is distributed unevenly, making the magnet leakage of the ending large; especially when the mover position changes, the leakage becomes more complex. It was observed that at different positions of the magnet as it moves (not shown), the effective magnetic flux changes and the difference produce the axial thrust. The FEA results in figure 4 illustrate that the leakage flux is higher in the case (a) because of the geometry of the core as can be seen from the figure. This is analogous to the stress concentration due to the shape of the geometry. The saturation flux exceeds the limit in the motor with extended teeth for the same output when compared to the motor with flat teeth. In figure 4(a), one of the ends of the outer core was subjected to magnetic saturation and it was attributed to the polarity of the input current and the magnetization of the permanent magnet. The PM was energized radially in the outward direction. When the current

polarity was altered, the saturation was observed on the other edge of the core. The motor geometry with flat teeth was far better in the point of view of magnetic saturation of the core as inferred from the FEA results.

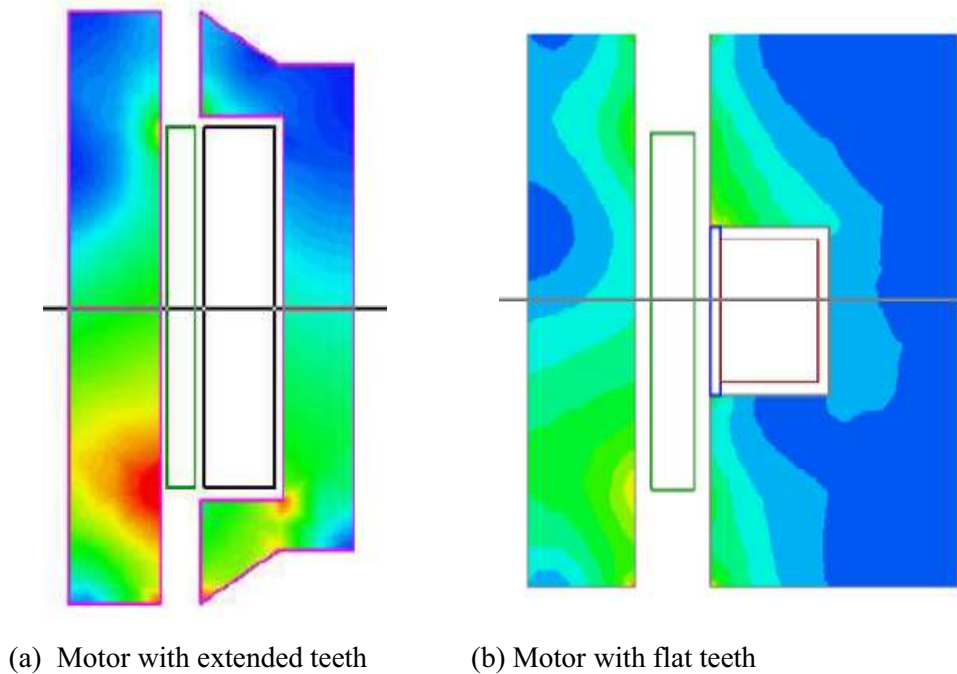(a) Motor with extended teeth   (b) Motor with flat teeth
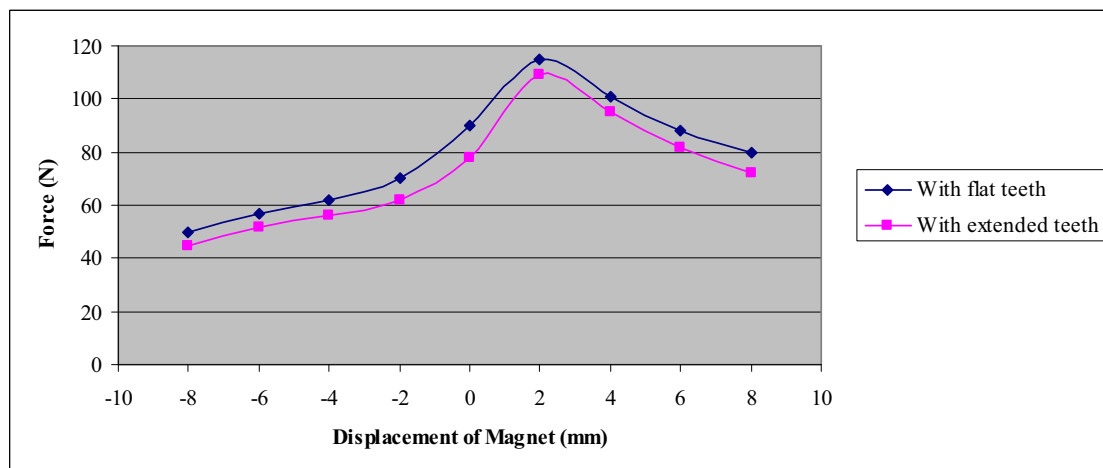
Figure 4. Magnetic field distribution.

Figure 5. Force generated at different PM positions.

Moreover, it was observed that the maximum force generated was higher for the motor with flat teeth. This was accounted for the effective production and utilization of the magnetic flux in the air gap. Figure 5 shows the variation of force generated at different magnet positions for two different cases. It was clear from the analysis that the maximum thrust force generated was dependent on the parameters of the motor, specifically, the relative position of the PM with respect to coil winding and core, the dimensions of coil and PM, shape and thickness of the core. The analysis has also been carried out by varying the core dimensions (the radial and axial), PM positions, and the current density

in the coil winding. The leakage flux is relatively higher in the motor with extended teeth and it will finally end up in a reduction in the effective axial force production.
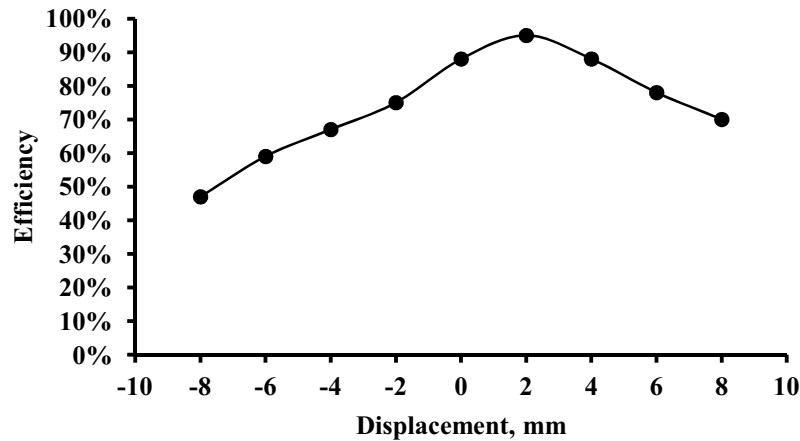

Figure 6. Motor efficiency at different magnet positions.

The force generated was different for different positions of the magnet. This was because of the difference in the superposed field distribution of magnet and the current carrying coil. The peak value of electromagnetic force reached when the magnet just begins its movement from the balanced position. In the present case, it's in the positive axial direction, again owing to the fact that the polarity of the current and the magnetization of PM. It was further attributed to the fact that the effective utilization of the flux flowing through the core and that generated in the current carrying coil. This is also in accordance with the parametric study conducted by the same authors earlier [8]. When the magnet moves away from the balanced position, the interaction of the magnetic fields (of coil and magnet) varies and hence the force. It was also observed that based on the direction of current supply in the coil, the force variation reverses. More clearly, we get an exact mirror image of the curve shown in figure 5, when the current polarity reverses (that is not shown here). Further, it was observed that even though a 40 mm long PM was deployed for action, there was only a little increase in the force generation. Consequently, when considering the compressor dynamics and efficiency and other aspects of design, it is recommended to adhere to a 30 mm long PM.
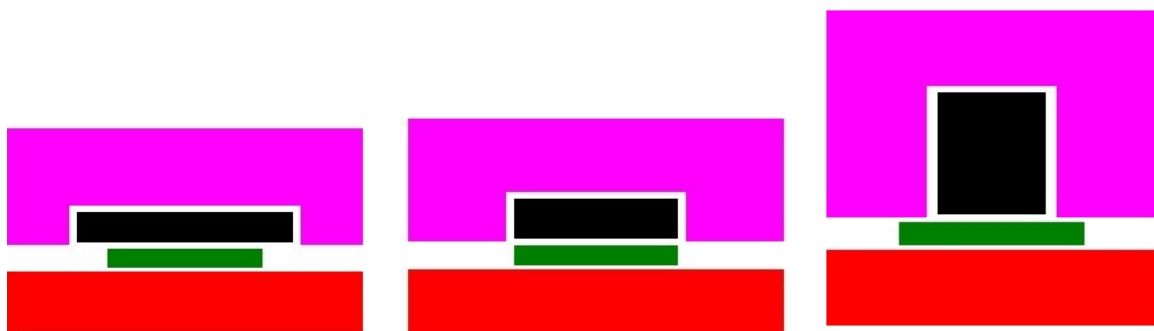

Figure 7. Variations of motor geometry by altering the coil and core dimensions.

Figure 7 presents the three variations of the motor in terms of relative dimensions of magnet, coil and the outer core. In all the variations, the magnet dimensions were kept constant. Accordingly, the outer diameter increases in order to accommodate the sufficient number of the coil winding. In the

first variation, the magnet was shorter than the coil winding where the effective utilisation of the air gap flux was least. The second variation shows the magnet directly under the coil winding in the balanced centre position. The third variation was modelled in such a way that the magnet comes under the influence of coil as well as outer core teeth in the balanced condition.
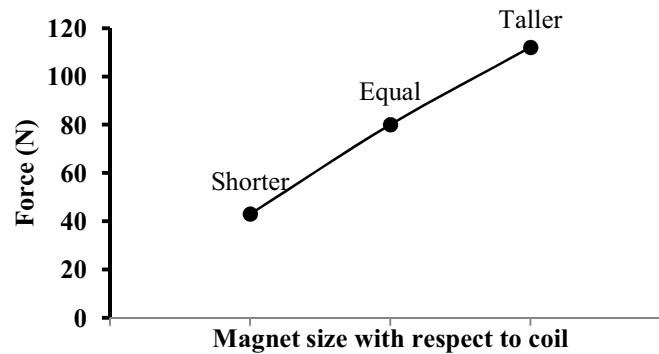

Figure 8. Electromagenetic force with magnet position relative to coil.

Figure 8 presents the thrust force generated in different cases described above. The higher maximum force was observed in a configuration where the permanent magnet was under the influence of coil and the static core in the initial condition. The maximum utilisation of the air gap flux density and the reduced magnetic losses were the factors lead to this higher force production.
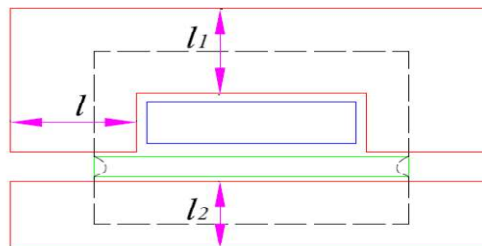

Figure 9. Dimensions of the core for the linear motor.

The dimensions of the inner and outer core of the motor are shown in Figure 9. The magnetic saturation thickness of the core l, l_1 and l_2 are evaluated theoretically using the electromagnetic equations. The saturation flux density of the core is given by equation (1),

$$B_{sat(core)} = \frac{\phi_{max}}{\pi(d_{0(mag)} + airgap)l} \qquad (1)$$

where the numerator represents the maximum flux available for use, $d_{0(mag)}$ is the outer diameter of the PM, *air gap* is the radial dimension of the air-gap between the cores and l is the saturation thickness [9].

A comparative analysis is conducted by using different core materials with the same radial dimension. The materials considered here are mild steel (MS) (B_s=1.85 T), steel 400 series (B_s=1.5 T), mu-metal (B_s=0.76 T), soft magnetic composite materials (B_s=1.6 T) and cold rolled grain oriented steel (CRGO steel) (B_s=2.01T). These materials are identified for analysis based on the commercial availability and from the limited literature. It is observed that if mild steel is employed as the core material, the core gets saturated easily. Therefore, it's not advisable to use MS as the core material. Mu-metal, with B_s=0.76 T, is also not suitable for this particular application of motor as the maximum

flux density measured is well above this value. It is not only the saturation level in the core needs to be considered, but at the same time, the required force is also to be generated with the selected core within the design constraints. Also, CRGO silicon steel is having reduced core losses, which makes it an ideal competitor to be used as core material in compact linear motors require long life.

When the magnet is displaced to either of the extreme ends of the yoke, the saturation levels in the yoke become the highest. Reducing the dimension l as well as l_2 results in magnetic saturation in the inner core. This would eventually lead to increased core losses. Reduction in l_1 does not have much effect on the saturation in the core, but the core becomes weaker. Another interesting observation from the analysis is that there is only 1-2% variation in the force developed when analyzed using different probable core materials.

4. Conclusions

The design and analysis of moving magnet type linear motor topology for Stirling coolers were presented. A range of geometric models of the motor was studied attentively and an assessment on them was presented. Out of the various geometries, the one which can keep the permanent magnet under the magnetic influence of the yoke even in the maximum displacement condition of the piston appears to be the better option in terms of electromagnetic thrust force, less leakage flux at the ends of the yoke, minimum core losses and with compact geometry. The influence of geometrical and electromagnetic parameters on the performance of the motor and the thrust force generation was presented and the suitable material combination for the motor was suggested. The rare-earth magnets selected are very light in weight with highest energy product, and hence this cooler is most suitable for weight sensitive applications such as electronic cooling in remote sensing and space science. From the comparative investigation of diverse core materials, it was concluded that cold rolled grain oriented silicon steel can be a healthier choice over the other alternatives considered based on the magnetic saturation levels in the core and the motor losses.

5. References

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