Proceedings Paper DOI: 10.58190/icat.2023.10

PROCEEDINGS OF

INTERNATIONAL CONFERENCE ON ADVANCED TECHNOLOGIES

https://proceedings.icatsconf.org/

11th International Conference on Advanced Technologies (ICAT'23), Istanbul-Turkiye, August 17-19, 2023.

Design and optimisation of tubular linear motor (TLM) for oxygen concentrator device

Şerafetdin BALOĞLU[+], İsmail SARITAŞ[*], Adem GÖLCÜK[**], Ali YAŞAR[#]

[+] Seydişehir District Directorate of National Education,
Seydişehir/Konya, Turkey
serefbal@gmail.com

[*]Department of Electrical and Electronics Engineering, Faculty of Technology,
Selcuk University,
Konya, Turkey
isaritas@selcuk.edu.tr

[**]Department of Biomedical Engineering, Faculty of Technology,
Selçuk University,
Konya, Turkey
adem.golcuk@selcuk.edu.tr

[#]Department of Mechatronics Engineering, Faculty of Technology,
Selçuk University,
Konya, Turkey
aliyasar@selcuk.edu.tr

Abstract **— Patients with chronic respiratory conditions such as Chronic Obstructive Pulmonary Disease (COPD) receive long-term oxygen therapy (USOT) to sustain their lives [1],[2]. With the development of oxygen concentrator (OC) devices that can produce the concentrated oxygen required for USOT, COPD patients are required to use these devices for more than 12 hours daily depending on the prescription [3],[4]. OC are medical devices that separate oxygen from the atmosphere using physical means to produce concentrated gas for medical purposes [5],[6]. The use of conventional motors based on the permanent magnetic rotary motor operating principle in OC devices increases the mass of the device and the operating noise disturbs the patients [3],[4],[7]. In this study, with the advances in magnet material, a tubular linear motor (TLM) structure with a strong, fixed coil moving permanent magnet, which is stronger than the linear motor used in many fields such as medical electronics, nanotechnology, defence industry, maglev trains, is designed and proposed for use in OK devices. It is difficult to optimise the TLM due to multiple design parameters and each parameter has a non-linear relationship with the static electromagnetic force. In this study, the thrust of the TLM is optimised by the finite element method (FEM) using the magnetic magnetostatic and transient solvers in Ansys Maxwell3D. Optimisation method based on FEM 3D model was used to optimise the design parameters. Comparing the pre- and post-optimisation of the TLM designed for use in the OC device, the thrust force was increased from 567.91 fN to 5.82 nN at the same working stroke distance.**

***Keywords*— Tubular linear motor, Oxygen concentrator, TLM, FEM, Optimization**

I. INTRODUCTION

Oxygen is an indispensable element for both healthy and sick individuals [5]. The expulsion of carbon dioxide, which is released during the transfer of atmospheric oxygen from the lung to the cell through the blood and the formation of energy in the mitochondria, through the lung is defined as respiration. If the wall of the alveoli in the lung, which absorbs oxygen from the air and transfers it to the blood, is damaged, it absorbs less oxygen. This is also called pulmonary emphysema [8]. COPD is a common, preventable and treatable disease associated with an increased chronic inflammatory response of the airway and lung to harmful particles and gases and is usually progressive, limiting permanent airflow [9],[10]. Direct and indirect treatment costs in COPD are increasing rapidly. Currently, the global economic cost of COPD is US$ 2.1 trillion and is estimated to be US$ 4.8 trillion by 2030 [11]. In adults over 40 years of age, the prevalence of COPD has been reported to be 11.7% in the world and 19.1% in Turkey with regional variations. In Turkey, deaths due to respiratory system diseases are the third leading cause of death and 45.6% of these deaths are due to COPD [12].

The most important aim of COPD treatment is to prolong life by improving quality of life. COPD treatment can be categorised under three headings: prevention of disease development (primary prevention), early diagnosis and disease prevention (secondary prevention), treatment of COPD and prevention of complications (tertiary prevention). As tertiary prevention methods, Pulmonary Rehabilitation, Long Term Oxygen Therapy (USOT), Non-Invasive Mechanical

Ventilation (NIMV), Surgical and Bronchoscopic Treatment of Emphysema can be counted [13].

Oxygen is considered a drug for medical use and must be prescribed by a physician [14]. The prescription specifies flow rates for different levels of activity and sleep. In such O_2 prescriptions, continuous oxygen flow rates are usually specified, taking into account the patients' past data and experience in USOT treatment.

In the literature, it is recommended that the most economical and suitable option for USOT is the OC device [15],[16]. The OC devices used today are both heavy and quite noisy due to the crankshaft classical compressor structure used in their structure [7],[17]. A study titled Evaluation of USOT Efficacy and Mortality was conducted on 112 COPD patients with a mean age of 70.52 ± 9.75 years. In this study, device noise, sleep irregularity, increased energy cost, nasal cannula discomfort, limitation of movement, headache and concern that the treatment would be addictive were reported as factors affecting compliance with USOT [3]. In another study, it was reported that 39% experienced problems during USOT and the noise factor caused by the device was pointed out among these problems [17],[18]. The efficacy of the long cannula was investigated in patients receiving USOT with a home OC device, and the use of long cannula-short cannula was followed up with pulse oximetry and ECG. No significant difference was found between O_2 saturation values. It was reported that patients' complaints about device noise decreased with the use of long cannula [4].

In the late 1970s, a satellite designed to study the Earth's atmosphere needed to cool a heated component. Oxford University began work on the development of linear machines. Since then, Oxford-type oil-free linear compressors have been widely used in Stirling cryocoolers [19]. In [20], the development of three models of Oxford-type moving-coil linear compressors was analysed. In [21], a new double vane compressor for electric vehicle air conditioning systems was designed and dynamically analysed. It is stated that the mechanical efficiency of the double vane compressor is better than that of the single vane compressor. In [22], with the support of the Republic of Turkey Ministry of Science, Industry and Technology and Arçelik A.Ş., the design and CAD model of a new moving magnet linear compressor for household refrigerators were presented. R600 refrigerant gas is compressed by the linear compressor. The accuracy of the analytical model presented is demonstrated.

II. Material and Method

Finite Element Method (FEM) is a method used by engineers, researchers and scientists to solve engineering problems from different fields. With FEM, which is used in the solution and design of electromagnetic problems, any engineering problem that can be defined by finite spatial partial differential equations with appropriate boundary and initial conditions can be solved. To give an example, when magnetic analyses of an existing cube-shaped electrical material are performed with FEM using Ansys Maxwell software; the cube material is divided into small pieces and Maxwell equations are solved in each of these small pieces. The basic equations of electromagnetics; Faraday's law of induction, Gauss's law of magnetism, Ampere's law, Gauss's law are used on small parts of the cube[23],[24].

A. *TLM Design*

In the literature, fixed coil moving magnet structures have been proposed in linear actuator studies in recent years. After NdFeB, samarium cobalt alloy magnets, neodymium, iron and boron elements are magnets with permanent induction and high energy. In actuators with moving coil structure, depending on the movement, there may be dispersion in the coil and breaks in the wires over time. For these reasons, TLM design with fixed coil-moving magnet structure was preferred.

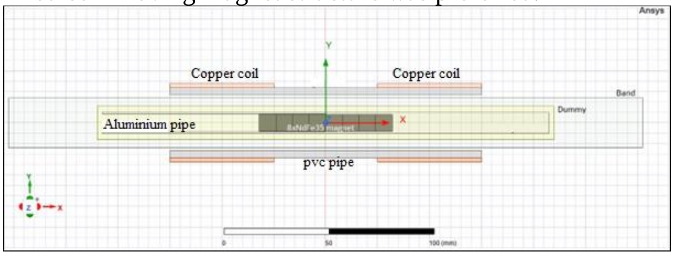


Fig. 1 2D Section View of the designed TLM

Orange coloured cylinders are copper coils with 300 spirals each. Two coils are connected in series. The coils are sectioned and then Separate Badies are applied and one terminal is left. Coils are wound on pvc pipe. 15V DC voltage was applied to the series connected coils during t and then the voltage was repeated periodically by changing the voltage polarity.

Since the number of moving parts in the design is more than 1, the vacuum material named Dummy is defined in the Band object. Dummy object contains 8 NdFe35 magnets (cylindrical 8x8 mm in size) and an aluminium pipe containing these magnets. Since the Maxwell software does not accept flat objects in the dummy object, the magnets and the pipe were chosen to be polygonal.

Within the Band structure, the Dummy object moves to the right and left (along the Y axis). There is no contact between Dummy and Band objects and sufficient movement space is left. The force parameter acting on the Dummy on the Y axis is calculated and graphed, and the eddy effects, magnetic field and lines are obtained as a result of the analysis.

In Fig.2, an external circuit diagram was designed to connect two separate coils used in maxwell 3d in series. The inductance of the coils wound in the laboratory environment was measured as 68uH and the ohmic resistance was measured as 3.4 Ω.

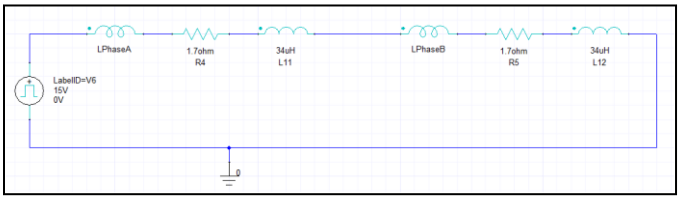


Fig. 2 External circuit diagram

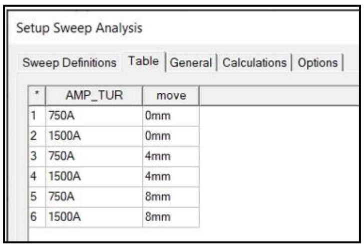
The design was subjected to Validation Check and it was seen that there was no error in the design. Thanks to the Motion Setup parameter setting, 30 mm movement of the Dummy object from the origin in the direction of the +y axis was provided.

B. *TLM Optimetrics Parameter Analysis*

The move parameter is defined in order to put distance between the magnets used in the design and to make analysis. Move parameter is set to be 0mm, 4mm and 8mm. For example, when move=8mm, the distance between the magnets is 8mm and the magnets are positioned at equal intervals along the +y and -y axes relative to the origin.

The magnetomotive force (F=N.I) in coils is defined as "ampere x turn" in Maxwell. For example, the value 1500 can be perceived as 1500 turns x 1 ampere or 750 turns x 2 amperes since there is no N (turn) unit. Since each of the coils in the design is 300 turns, it is accepted here as 300 turns x 2.5 A. In order to analyse the variation of the force F according to the applied current value, another parameter named AMP_TUR is defined. This parameter took two different values, 750 and 1500.

According to the values of Move and AMP_TUR parameters, 6 iterations were formed. The analysis of the force force in maxwell3d was completed in about 5 hours.


Setup Sweep Analysis

Sweep Definitions | Table | General | Calculations | Options

*	AMP_TUR	move
1	750A	0mm
2	1500A	0mm
3	750A	4mm
4	1500A	4mm
5	750A	8mm
6	1500A	8mm

Fig. 3 Optimetrics parameters and their values

Fig. 4-6 shows the positions of the magnets according to the value of the move parameter.

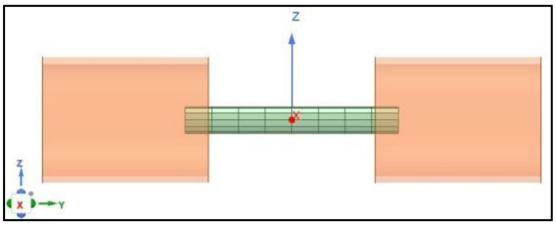


Fig. 4 Position of coils and magnets when Move=0mm

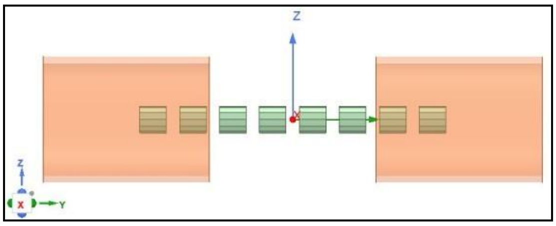


Fig. 5 Position of coils and magnets when Move=4mm

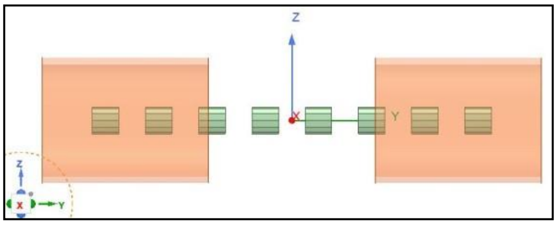


Fig. 6 Position of coils and magnets when Move=8mm

III. Results

In the design, the distance between the coils and the width of each coil is 50 mm and the total length of the magnets is 64 mm. When the Force_Y graph given in Fig. 7 is analysed, the maximum force on the +y axis is 567.91fN when AMP_TUR=750, move=0mm. Since the force in the direction of movement of the TLM will be taken as basis, it is understood from the two-parameter optimetrics parameter analysis that there is a correlation between the maximum force that can be measured in the y-axis analysis and the coil width and magnet width.

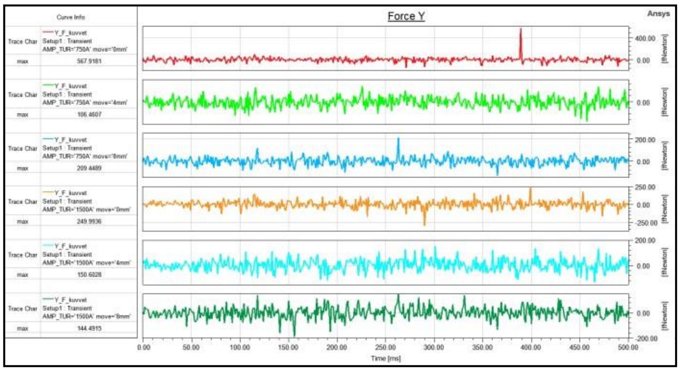
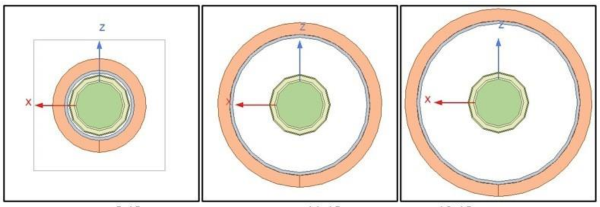


Fig. 7 Optimetric analysis of the force on the y-axis with respect to time

The thickness of the pvc pipe material in which the coils are wound is reduced from 3.4 mm to 0.5 mm, provided that the parameters AMP_TUR=750, move=0mm remain constant. The effect of the air gap between the dummy object and the coils on the force on the +y axis was investigated.



r=5.45 mm r=11.45 mm r=13.45 mm

Fig. 8 TLM diameter and air clearance

The optimetric analysis of the half diameter parameter r was performed in 9 iterations with 1 mm increments in the range of 5.45 mm-13.45 mm and took 4 hours. In Fig. 9, the effect of r parameter change on Fy force is analysed. The maximum value of Fy force was 5.8225 nN at 47 ms when r=11,45 mm. The Fy force at r=11,45mm given in Fig. 9 created an instantaneous thrust force without vibration.

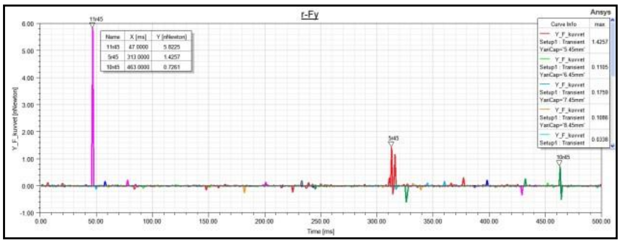


Fig. 9 Analysis of r-Fy change with respect to time

After the optimisation study, Table 1 shows the thrust force generated by the TLM in the y-axis direction and the values of other parameters before and after the optimetric parameter analysis.

TABLE I
TLM OPTIMETRIC PARAMETER VALUES BEFORE AND AFTER ANALYSIS

Parameter Name	Pre-Design			Post-Design		
	Value	**Unit**	**Fy_{max}**	**Value**	**Unit**	**Fy_{max}**
move	0	mm	567,91 fN	0	mm	5.82 nN
Amp_tur	750	ampertur		750	ampertur	
Pvc thickness	3.4	mm		0.5	mm	
r yarıçap	5.45	mm		11.45	mm	

In the studies carried out to optimise the magnetomotive force in TLM, it has been determined that the amperextur parameter is directly proportional. If the current value applied to the coils of the motor and the number of coil spirals are increased, the thrust produced by the TLM increases. When the thickness of the non-ferromagnetic material used in the simulation and on which the coils are wound is reduced, the magnetomotive force increased. There is a non-linear relationship between the gap between magnets and electromagnetic force.

IV. Conclusions

Oxygen is a basic medical requirement for patients in mild and/or severe cases. The demand and supply for OC devices has increased significantly recently due to the Covid-19 outbreak, etc. It has advantages such as the ease of receiving O_2 therapy in the patient's home environment and the OK device can operate for thousands of hours. However, the noise of the device has been the subject of many complaints and many studies have been conducted. TLM motor was proposed instead of the conventional motor used in these devices and electromagnetic analyses of the structures and motor parameters were successfully optimised. In the future, OC devices have the potential to be used more effectively by reducing the noise and reducing the size with the development of magnets and the widespread use of TLM technology motors. The OC devices with TLM can be synchronised with the studies given in[25] and it can be observed whether the desired patient O_2 saturation level is reached.

Acknowledgment

This study is supported by Selcuk University Scientific Research Projects (BAP) Coordinatorship project number 22401005 and Scientific and Technological Research Council of Turkey (TÜBİTAK) 1002-B Emergency Support Module project number 123E053.

References

[1] Group*, N.O.T.T., *Continuous or nocturnal oxygen therapy in hypoxemic chronic obstructive lung disease: a clinical trial.* Annals of internal medicine, 1980. **93**(3): p. 391-398.

[2] Tanrıverdi, E., *Evde Oksijen Konsantratörü İle Sürekli Oksijen Tedavisi Alan Hastalarda Uzun Kanül Kullanımının Güvenilirliği*, in *Göğüs Hastalıkları Kliniği*. 2010, Sağlık Bakanlığı Ankara Atatürk Eğitim Ve Araştırma Hastanesi,YÖK Tez Merkezi. p. 88.

[3] Türkoğlu, N., et al., *Evaluating the Efficiency of Long Term Oxygen Therapy and Mortality in Chronic Obstructive Pulmonary Disease.* European Journal of General Medicine, 2015. **12**(1).

[4] Tanrıverdi, E. and H.C. Hasanoğlu, *Evde oksijen konsantratörü ile oksijen tedavisi alan hastalarda uzun kanül kullanımının güvenilirliği.* Göztepe Tıp Dergisi, 2013. **28**(4): p. 186-193.

[5] Yadav, V.K., et al., *Recent trends in the nanozeolites-based oxygen concentrators and their application in respiratory disorders.* Frontiers in Medicine, 2023. **10**: p. 1147373.

[6] Nowadly, C.D., et al., *The use of portable oxygen concentrators in low-resource settings: a systematic review.* Prehospital and Disaster Medicine, 2022. **37**(2): p. 247-254.

[7] Atacak, I., M. Korkusuz, and O.F. Bay, *Design and Implementation of an Oxygen Concentrator with Gprs-Based Fault Transfer System.* Journal of Mechanics in Medicine and Biology, 2012. **12**(4): p. 1250060.

[8] (2011) The LongFonds website. [Online]. Available: https://www.youtube.com/watch?v=sslm9i9njeY.

[9] Menekşe, D.T.S., *Acil Servise Nefes Darlığı İle Başvuran Kronik Obstrüktif Akciğer Hastalığı Olan Hastalarda Oxymask® İle Hazneli Basit Oksijen Maskesinin Kan Gazı Değerleri Üzerine Etkinliklerinin Karşılaştırılması*, in *Tıp Fakültesi,Acil Tıp Anabilim Dalı*. 2020, Atatürk Üniversitesi: YÖK Tez Merkezi. p. 100.

[10] Oyman, G.T., *Stabil dönemde eozinofilik ve non-eozinofilik KOAH'lılardaklinik, fonksiyonel ve sistemik inflamatuar parametreler.* 2019.

[11] Bloom, D.E., et al., *The global economic burden of noncommunicable diseases*. 2012, Program on the Global Demography of Aging.

[12] Türk Toraks Derneği. (*2020) toraks* homepage on news. [Online]. Available: https://www.toraks.org.tr/site/news/10102.

[13] Grubu, T.T.D.K.Ç., *Kronik Obstrüktİf Akciğer Hastalığı (KOAH) Koruma, Tanı ve Tedavi Raporu*. 2014: ADA Ofset Matbaacılık Tic. Ltd. Şti., Litros Yolu 2. Matbaacılar S. E Blok No: (ZE2) 1. Kat Topkapı, İstanbul. p. 85.

[14] Dunne, P.J., *The clinical impact of new long-term oxygen therapy technology.* Respiratory Care, 2009. **54**(8): p. 1100-1111.

[15] Restrick, L., et al., *Assessment and follow up of patients prescribed long term oxygen treatment.* Thorax, 1993. **48**(7): p. 708-713.

[16] Fauroux, B., P. Howard, and J. Muir, *Home treatment for chronic respiratory insufficiency: the situation in Europe in 1992. The European Working Group on Home Treatment for Chronic Respiratory Insufficiency.* European Respiratory Journal, 1994. **7**(9): p. 1721-1726.

[17] Atacak, İ. and M. Korkusuz, *Oksijen Konsantratörlerinin Yapısal Sorunlarına Yönelik Çözüm Önerileri.* Engineering Sciences, 2011. **6**(4): p. 768-777.

[18] Pekçalıskan K., N., et al., *Uzun süreli oksijen tedavisinin etkinliği ve hasta uyumu.* Toraks Dergisi, 2007. **8**: p. 163-9.

[19] Bailey, P., et al., *High performance flight cryocooler compressor*, in *Cryocoolers 11*. 2002, Springer. p. 169-174.

[20] Liang, K., M. Dadd, and P. Bailey, *Clearance seal compressors with linear motor drives. Part 1: Background and system analysis.*

Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2013. **227**(3): p. 242-251.

[21] Yang, X., C. Dong, and Z. Qu, *Design and dynamic analysis of a novel double-swing vane compressor for electric vehicle air conditioning systems.* International Journal of Refrigeration, 2017. **76**: p. 52-62.

[22] Bijanzad, A., et al., *Development of a new moving magnet linear compressor. Part A: Design and modeling.* International Journal of Refrigeration, 2020. **113**: p. 70-79.

[23] Taşkın, Ö., *Çift Taraflı Hava Çekirdekli Lineer Motor Tasarımı Ve Gerçeklenmesi*. 2015, Fen Bilimleri Enstitüsü.

[24] Oğuz, K., *Çift taraflı hava çekirdekli sabit mıknatıslı lineer servo motor tasarımı ve uygulaması*. 2021.

[25] Baloglu, S., I. Saritas, and A. Golcuk. *Design and Implementation of Pulse Oximeter Synchronized with Respirators*. in *2022 57th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*. 2022. IEEE.