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Development of a Prototype Radio-Frequency Cathode with Ferrite Core for Use in Space Propulsion Applications as Electron Source

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Final Technical Report

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ABSTRACT

The objective of this Grant was the design, manufacture and test a prototype radio-frequency cathode with ferrite core for use in space propulsion applications as electron source. Plasma cathode can be used as electron sources in electric propulsion applications. Unlike hollow cathodes where a low work function insert material that needs to be heated to elevated temperatures is utilized for the electron emission, plasma cathodes do not need to be preheated, and could be switched on instantaneously. At the Bogazici University Space Technologies Laboratory (BUSTLab), radio frequency (RF) plasma cathode devices for use as electron sources of plasma thrusters have been studied, manufactured and successfully tested. Introduction of a ferromagnetic core enhances the power transfer efficiency of the inductively coupled plasma (ICP). As part of the research conducted under this Grant, we designed, manufactured and tested of several radio-frequency cathodes, with standard coil antennae and with Mn-Zn ferrite core, for use in space propulsion applications as an electron source. The extracted electron current, electron extraction cost and gas utilization factor for the developed plasma cathodes have been studied. This Report summarizes these accomplishments. References to the published and soon-to-be-published work are provided.

Keywords: electric propulsion, RF plasma, ferrite core, neutralizer cathode

INTRODUCTION

For spacecraft electric propulsion applications, hollow cathodes where a low work function emitter material is used for the thermionic emission of electrons are typically used [1, 2]. In typical hollow cathodes, usually, a wire is wound around the region where the thermionic emitter material is placed, in order to increase the temperature of the thermionic emitter material. Depending on the work function of the thermionic emitter material, after a certain critical temperature the thermionic electron emission at the desired current per unit area intensity from the surface of this insert material commence. Hence, the electron extraction from the hollow cathodes is achieved. However, there is a growing interest in using plasma cathode devices as alternatives to hollow cathodes. In plasma cathode devices, plasma is generated in a small chamber and electrons are extracted out of this plasma chamber through an orifice opening on the front chamber wall [3]. Plasma cathodes can be switched on in a much shorter time when compared with hollow cathodes where the thermionic emitter material needs to be preheated to elevated temperatures [4]. In plasma cathode devices, for the generation of the plasma, different plasma generation methods such as radio frequency CCP [5] or ICP [6, 7], microwave (ECR) [8, 9] and helicon [10] have been employed.

At the Bogazici University Space Technologies Laboratory (BUSTLab), different designs of radio frequency (RF) plasma cathode devices for use as electron sources of plasma thrusters had been studied, designed, manufactured and tested. A representative 2D technical drawing of one of those RF plasma cathodes, developed at BUSTLab, is shown in Figure 1. The concept of that design was taken from Hatakeyama *et al.*'s study [6]. That shown RF plasma cathode had a cylindrical pyrex chamber with a gas inlet at the back wall. A machinable glass ceramic (MGC) front plate was attached to the front side of the chamber. The chamber was extended out to the sides at its end, so that an o-ring between the extended part and the front plate could seal gas inside the chamber. A 0.5 mm thick molybdenum cylindrical electrode was placed on the inside wall of the chamber as an ion collector electrode and was connected to ground using a thin wire. RF coil, pyrex chamber and front plate are mounted on a teflon backplate.

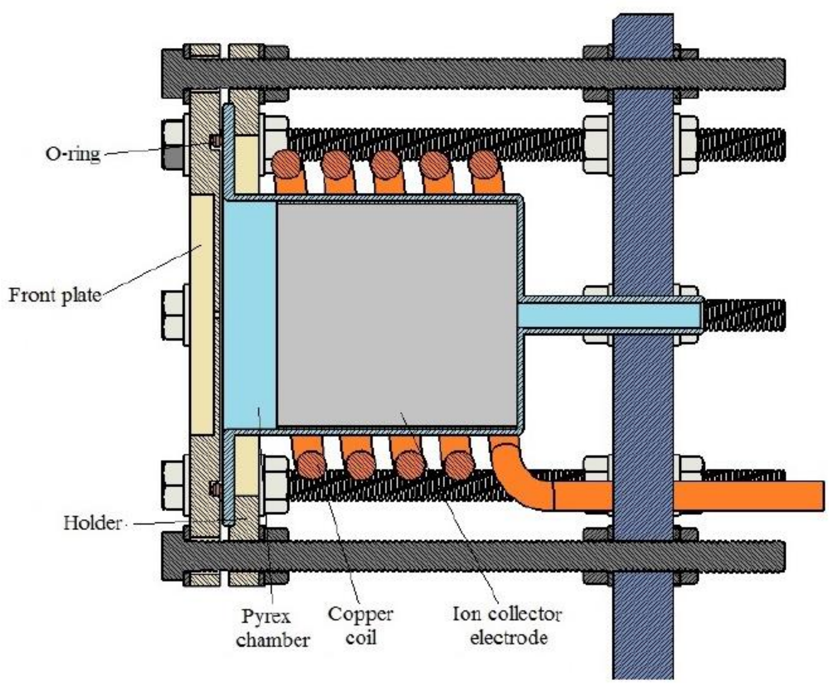

Figure.1 2D drawing of one of the earlier RF plasma cathodes studied and tested at BUSTLab

In some of those earlier studies, effect of four geometric parameters: chamber diameter and chamber length, and orifice diameter and orifice length on the plasma generation and electron extraction characteristics of the RF plasma cathode device had been investigated [11]. In addition, Langmuir probe measurements had been conducted to investigate the properties of the RF plasma generated inside the RF plasma cathode, and to determine the change of these properties by the variation of the mass flow rate and RF power.

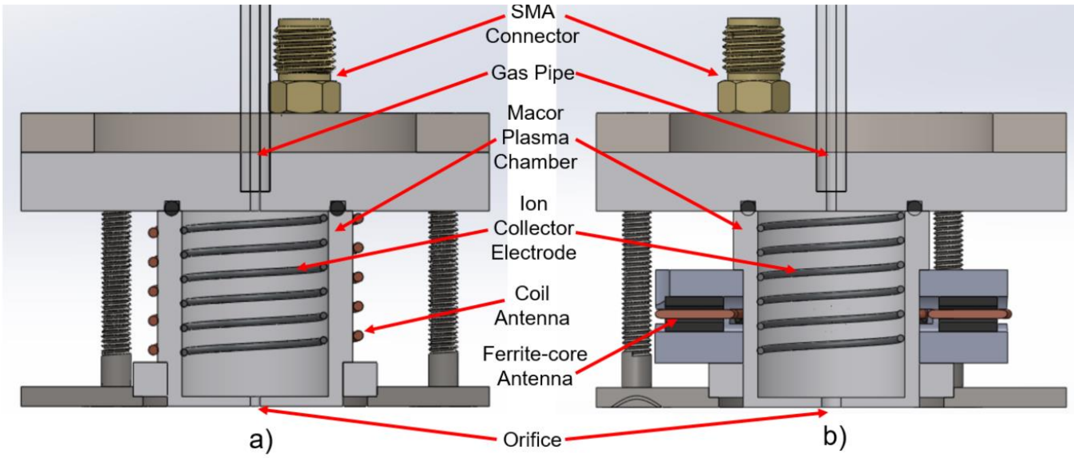

Figure 2. Cross-sectional drawing of the a) RF plasma cathode with a standard coil antenna b) RF plasma cathode with a ferrite core antenna

In a plasma cathode device, there are two major processes: plasma generation and electron extraction. It is proposed that by adding a ferrite core in the antenna, the RF power coupling to the plasma can be increased considerably, and the power efficiency for plasma generation can be improved significantly [12, 13, 14, 15]. Recently, several more radio frequency (RF) plasma cathode devices for use as electron sources of plasma thrusters have been studied at BUSTLab. As part of one of these studies, two RF plasma cathodes, one with a standard five turn coil antenna, similar to an earlier work [11], and the other with a single turn ferrite core antenna have been designed, manufactured and experimentally studied, with Argon propellant, in order to understand the effects of ferrite core in improving the RF power coupling to the plasma and increasing the mass utilization efficiency of the device.

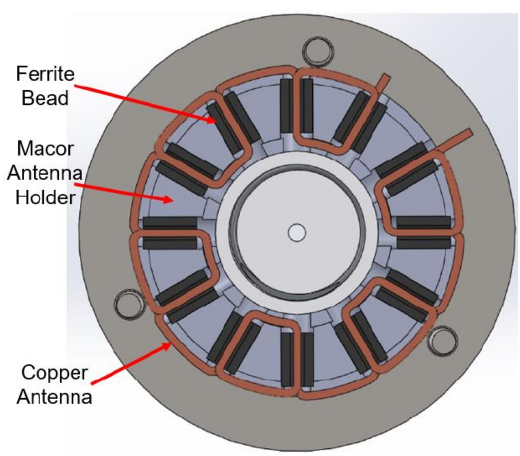

Figure 3. Cross-sectional drawing of the structure of the ferrite core antenna

Drawings of the built RF plasma cathode devices are shown in Figure 2. Figure 2a shows the cathode with a coil antenna, whereas in Figure 2b, the cathode with an antenna where a novel design of ferrite materials in desired orientations (as shown in Figure 3) is shown.

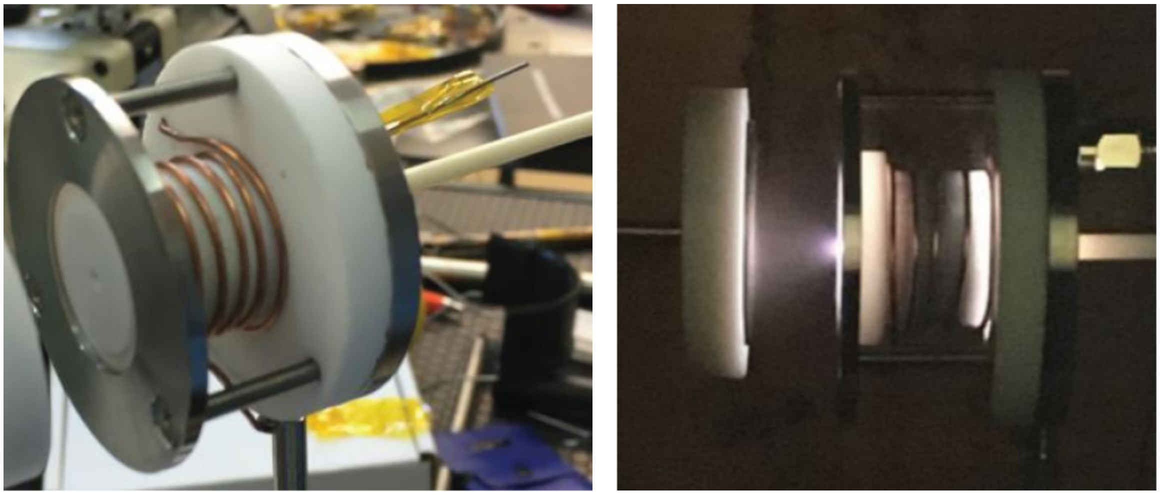

Figure 4. Pictures of the ICP plasma cathode with 5 turn coil antenna. The ICP cathode at operation inside vacuum chamber (right).

The manufactured RF plasma cathodes have cup-shaped macor chambers with inner diameter of 15 mm and length of 19 mm. The chamber has a 1.2 mm diameter orifice on the front wall. This macor chamber is placed on a macor back plate with a 1/8 inch gas inlet, and a groove for an O-ring of 16 mm diameter at 1.5 mm thickness. The chamber is secured on the back plate with the help of a set of stainless-steel rings bolted to each other with the help of three long M3 screws. A coil shaped 0.7 mm thick molybdenum wire is placed on the inside wall of the chamber as the ion collector electrode. There is a small hole on the backplate aligned with the inside wall of the chamber to allow the connection of this ion collector coil to ground using a thin wire. This hole is sealed using epoxy glue. The RF antenna is attached to an SMA connector placed at the backplate: one lead of the antenna wire is connected to the center pin and the other end of the antenna is connected to the outer case of the SMA connector. The SMA connector is screwed to the back plate through. For the experiments, the area of the coil shaped ion collector is estimated to be 5.8 cm^2.

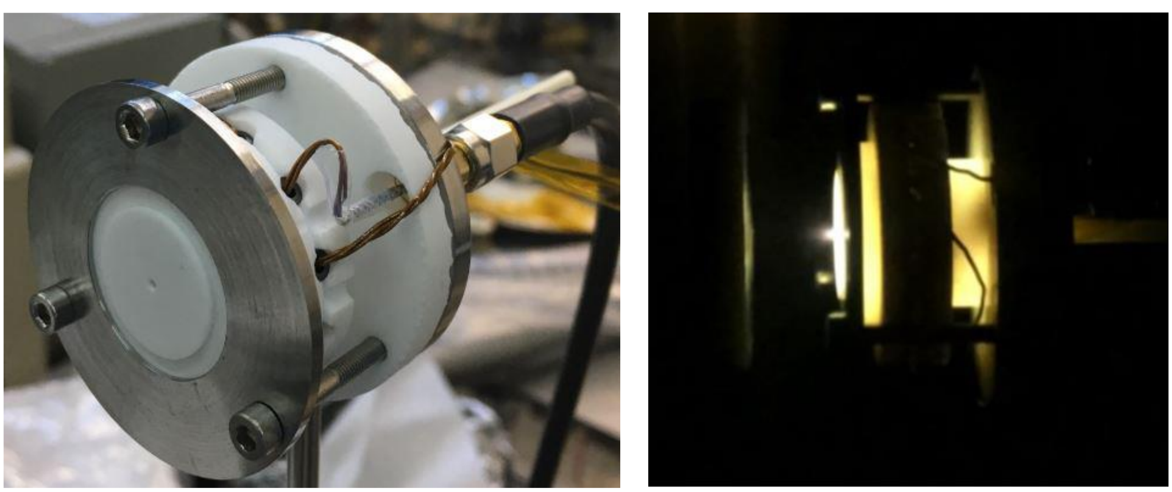

Figure 5. Pictures of the plasma cathode with ferrite core antenna. The ferrite cathode at operation inside vacuum chamber (right).

For the cathode with a standard coil antenna, a helical 5 turn copper wire of 1 mm diameter is used (Figure 4). For the cathode with ferrite core antenna, copper wire of 0.7 mm in diameter is wound around a specially machined macor piece where 12 Mn-Zn ferrite tubes of 1.75 mm inner diameter, 3.5 mm outer diameter and 6 mm of length are placed in radial directions as shown in Figure 5.

MAGNETIC INSULATORS

Most known magnetic materials are good conductors and have high saturation magnetization. Therefore, these are not suitable for high frequency operation where the core material can overheat quickly above the Curie temperature making them useless as a core material. Insulating magnetic materials exist in several crystalline forms. For example, the hexaferrites are the main type of hard magnets used in permanent magnet applications. Manganese and Nickel-Zinc Ferrites are cubic in crystal structure and therefore are soft magnets (i.e. low coercivity). These soft magnetic insulators are suitable for high frequency applications owing to their high resistivity. There is a common relationship for magnetic materials between their resistivity and saturation magnetization. The higher the magnetization the lower the electrical resistivity of the magnetic material. This is true for both conducting and insulating magnetic materials. Therefore, one has to use a core material for a specific frequency for a specific need in saturation magnetization which directly influences the amplitude of the high frequency magnetic field.

Soft magnetic oxides are available in different crystal structures. The pertinent ones here are materials having cubic crystal structures. These are ferrites and garnets. Their magnetic structure is ferrimagnetic and therefore the net magnetization is much smaller than those of metallic magnets.

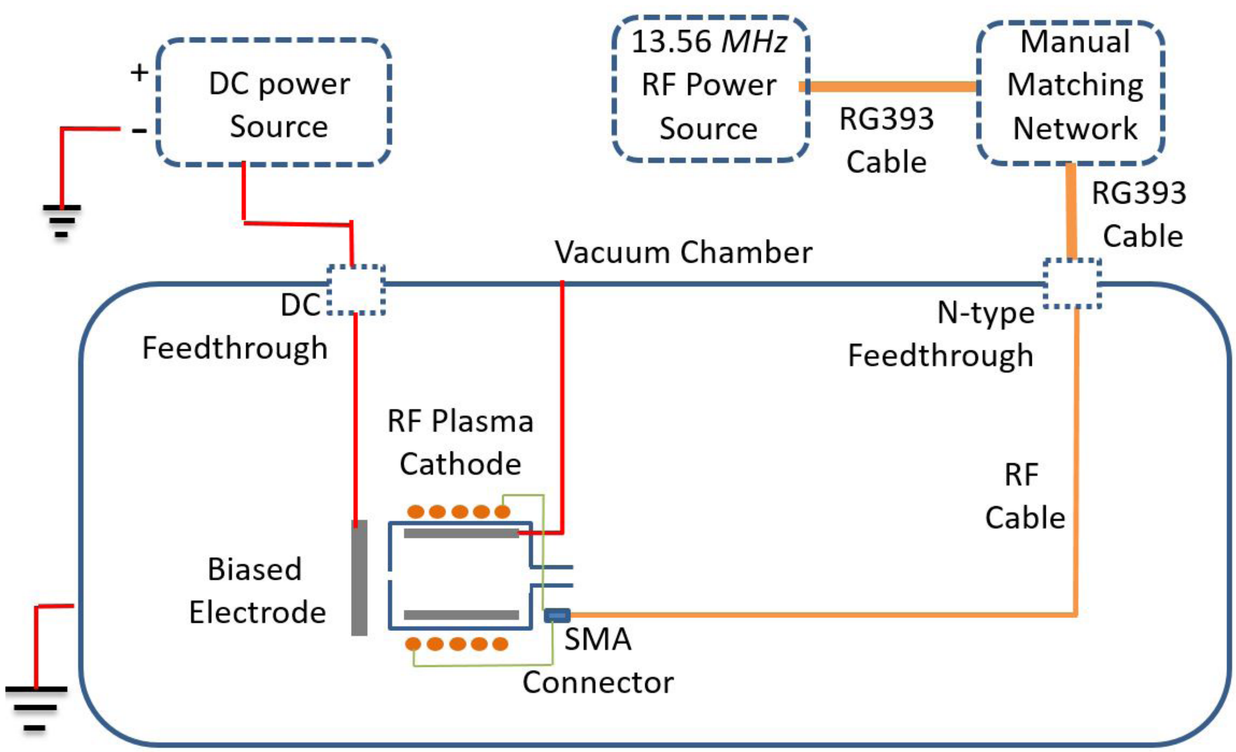

Figure 6. Experimental setup of the RF plasma cathode experiments

Two types of soft magnetic ferrites are used very commonly in high frequency applications. Manganese-Zinc Ferrites have low resistivity (20 -100 Ohm.cm), high permeability and high magnetization (460 mT) and are preferred for frequencies less than 2 MHz. Nickel-Zinc Ferrites have lower permeability and lower magnetization (220 mT) therefore much higher resistivities (10-20 kOhm.cm), which makes nickel ferrites more suitable for frequencies between 2-100MHz. Rare earth Iron Garnets are suitable for even much higher frequencies in the microwave region owing to their much higher resistivities combined with high permeability.

EXPERIMENTAL MEASUREMENTS AND DISCUSSIONS

The experimental measurements have been conducted inside the BUSTLab vacuum chamber [16]. During the tests, the vacuum level of this 1.5 m diameter, 2.7 m long cylindrical chamber has been kept on the order of 1.7 x 10^{-5} Torr for 4 sccm argon flow rate. A schematic of the experimental setup is shown in Figure 6. Coaxial RG393 cables with N-type connectors are used to carry the RF power from the power supply to the vacuum feedthrough through a manual matching network. For the extraction of the electron current from the cathode, a 4 cm diameter stainless steel electrode is placed 12 mm in front of the orifice region as shown in Figure 6. This electrode is connected to a DC power supply. As expressed in previous parts, operation of a RF plasma cathode device consists of two parts: plasma generation and electron extraction. During the experimental studies, the matching network was used to find the best matching capacitor and inductor settings for the given antenna and plasma conditions. During the experiments the argon mass flow rate is set to a constant value, and an ICP plasma is generated inside the chamber. After this procedure, the collector electrode facing RF cathode with ferrite core is biased at a positive voltage and the extracted electron current values are recorded for varying propellant flow rate, RF power to the antenna and electrode potential values.

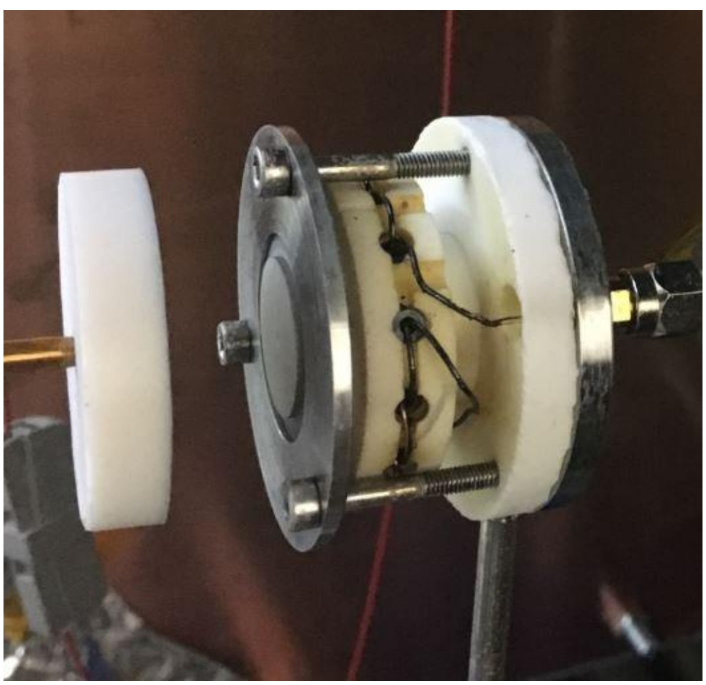

Figure 7. The ferrite core plasma cathode with the biased electrode placed in front of the orifice region

Electron temperature and electron density values are measured by a home-built double Langmuir probe. A low pass filter with a cut-off frequency of 1.9 MHz is placed between the probe and the voltage source in order to minimize the potential fluctuations.

The measured values are compared with similar studies form the literature as presented in Table 1. The electron extraction cost is defined as the power required for the plasma production and the extraction of 1 A of electron current. The gas utilization factor indicates the average number of times that an atom repeats ionization/recombination while it stays inside the discharge chamber [6].

Table 1. Comparison of the performance parameters for the plasma cathodes with and without ferrite core [17]

Device	Propellant	Volume Flow Rate [sccm]	Extracted Current [mA]	Electron Extraction Cost [W/A]	Gas Utilization Factor
RF cathode with single turn ferrite core antenna	Argon	9	1420	216	2.21
RF cathode with five turn coil antenna	Argon	4	780	182	2.73
RF cathode by Hatekeyama[6]	Xenon	2.0	1500	93	10.6
RF cathode by Longmier[10]	Argon	15	3500	186	3.8
RF cathode by Weis[5]	Xenon	1.5	100	510	0.37

Even though, with this design, the presented novel single turn ferrite core antenna design does not decrease the power coupling to the plasma, reducing the electron extraction cost, studies and tests with alternative designs are ongoing.

RESEARCH ACTIVITIES

Studies on ferrite core plasma cathode are still ongoing, and new and novel design are in the process of being tested. We expect to submit another journal paper in the next several months.

As part of this project, we have presented our research at two international conferences:

Celik M., Kurt H., Ferromagnetic Enhanced Inductively Coupled Plasma Cathode for Thruster Ion Neutralization, 17th International Conference on Ion Sources (ICIS), Poster Presentation, Geneva, Switzerland, October 2017.

Celik M., Kurt H., Frequency Dependence of Electron Yield in a Ferrite Core RF Cathode to be used in Plasma Thrusters, 7th Russian-German Conference on Electric Propulsion (RGCEP), Oral Presentation, Dresden, Germany, October 2018.

Part of the initial studies is published, and part of another work is about to be submitted for publication:

Celik, M., Kurt, H., *Ferromagnetic Enhanced Inductively Coupled Plasma Cathode for Thruster Ion Neutralization*, AIP Conference Proceedings, Vol. 2011, 090022, September 2018

Kokal, U., Uc I.S., Celik M., *Experimental Studies of the Frequency Dependence of Electron Yield in a Ferrite Core RF Cathode with Internal Antenna Design to be used in Plasma Thrusters*, in preparation to be submitted to Review of Scientific Instruments

As part of this projects two graduate students were supported:

Ugur Kokal, M.Sc. Student, Bogazici University, Department of Mechanical Engineering, Istanbul, Turkey

Abdurrahman Turkmen, M.Sc. Student, Istanbul Technical University, Department of Mechanical Engineering, Istanbul, Turkey

Additionally, as part of this project three undergraduate students of Bogazici University, Department of Mechanical Engineering were partially supported:

Enes Oguz Iskender, Undergraduate Student, Bogazici University, Department of Mechanical Engineering, Istanbul, Turkey

Tugrul Tamer Coskun, Undergraduate Student, Bogazici University, Department of Mechanical Engineering, Istanbul, Turkey

Ege Apaydin, Undergraduate Student, Bogazici University, Department of Mechanical Engineering, Istanbul, Turkey

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