DESIGN OF A THERMOPHORETIC SAMPLING SYSTEM TO COLLECT SOOT FROM FLAMES

by

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ABSTRACT

Project Objective

Design a thermophoretic sampling system and purchase all required material and equipment for the design.

Methodology to be Adopted

Study the systems available in the market and design the most effective and cost-efficient system. It includes studying different motors and associated components that are available in the market and selecting the right components to suit the purpose.

Brief Summary of the Project

The report discusses the planning phase of the project to the end of the design phase along with a few suggestions for a further scope of work. This project includes choosing the best system to design with-in the few well-known existing models such as the multi-probe system, pneumatic and electric linear motor system, amongst others. After considering multiple factors, an electric linear motor configuration architect was chosen for the design. The secondary research is to find the right motor (stator), slider, servo drive, trailing chain cable, power supply, lubricant, USB interface converter, tweezer, set screw, washer, thin hex nut, gasket sealant and a novel designed tweezer holder according to the design requirement and fabrication ease. The major objective of the design is to achieve an ultra-high-speed stroke with a residue time as little as 3ms to 100ms for collecting soot from different flames. Another novel highlight of the project was the TEM mesh (micro-grid) holder using a tweezer and an in-house designed tweezer holder. All the required purchase orders are placed for the components needed for designed thermophoretic sampling device.

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1 INTRODUCTION

The project objective is to design a thermophoretic sampling system (TSS) to collect soot particles using transmission electron microscope (TEM) micro grid in different fuel flames. This system is like a robotic arm with two degrees of freedom motion. One is the linear motion front & back and other is rotational, when the system needs a 90° degree rotation. This system is integrated to a burner system where the burner can move up and down because of which TSS complexity reduced to two degree of freedom. The main design objective was to achieve an ultra high-speed stroke where the system can achieve a residue time for collecting soot particle that can vary from 3ms to 100ms. It is imperative at no point the soot collected on micro grid is neither too less nor fully over loaded. Emitting soot depends on the fuel properties hence the design should have a capability to alter the residue time. In order to achieve this kind of high-speed stroke we needed a LinMot liner motor that can generate a force of at least 65N that can also move with a speed of at least 7m/s.

1.1 LITERATURE REVIEW

After looking at the existing literature, we were able to identify three systems; the first system is a pneumatic system, the second system is a multi-probe system using stepper motor and the last system is an electric system using a linear motor.

1.1.1 PNEUMATIC SYSTEM ARCHITECT

Changshu Institute of Technology, China, used a system that needed a standalone N2 cylinder

Figure 1 Pneumatic System TSS used by Changshu Institute of Technology [1]

for operating TSS along with the other cylinders for combustion process[1], but what we observed that this pneumatic system design was only able to achieve a sampling residence time of 37ms at 10bar[1]

The other pneumatic system that was researched was used by the University of Duisburg, Germany, which was a much more complicated system using a piston configuration but still it can only achieve residue time with a range from 67 to 1873 ms[2]. Our design objective is to achieve ultra high-speed stroke with a residue time of 3ms which cannot be achieved with these designs.

Figure 2 Pneumatic system with piston configuration used by University of Duisburg[2]

This system also consists of pneumatic cylinder which could generate a maximum force of 612 N at 6 bar and 1181N at 10bar pressure. The burner configuration of this system is different from our existing design. This design was not a consideration for our project.

1.1.2 MULTI-PROBE SYSTEM

The University of Toronto designed a sophisticated system with a multi-probe architect[3] which is driven by a stepper motor, where multiple samples can be taken at different intervals of time. This configuration has precision control with a sampling residue time of 2.6ms, which is also capable of collecting 10 samples in a single run. This system was designed for a high-pressure chamber where samples can be collected in laminar diffusion flames up to 100 atm. This system has the sampling circular disc, attached to a gear box with 10:1

Figure 3 Multiple Probe system using stepper motor used by University of Toronto [3]

1.1.3 LINEAR MOTOR SYSTEM

The Review of Scientific Instruments Journal published a paper on an electric thermophoretic sampling device in Dec 2016, and this device used a linear motor from LinMot[4]

Figure 4 Electric Thermophoretic sampling device using linear motor [4]

This system consists of an electric motor connected to an electronic servo drive and a power supply. Servo drive helps the motor to operate across its force and velocity ranges according to the

inputted instruction in the program. Path, speed, orientation can be sequenced using the program available with servo drive during the configuration of linear motor. Maximum speed achieved by the motor is one of the key design parameters that is directly translated into residue time. Speed and position of the slider can be easily altered as per the experiment requirement with help of a software associated with servo drive and motor.

This electric design architect inspired us to make similar system as it is very easy to construct and would meet our design requirements. Its also easy to vary the speed of the stroke using the software associated with the motor and the servo drive by which residue time can be changed. Our experimental setup is made to test different fuels, based on fuel properties time required to the collect the soot varies. Having an option to adjust the stroke speed would enable the system to operate at required residue time varying from 3ms to 100ms. Hence, we came up with a similar design as shown in Figure 5 following chapter would discuss the design in detail.

Figure 5 Designed thermophoretic sampling device (TSD) for our project

1.2 INTRODUCTION TO SOOT

Our main objective is to collect soot in burning flames of different fuel. In this project, we designed a thermophoretic sampling device to do the same. In layman language, the black carbon that is formed on a spoon when it is placed over the candlelight is called soot. It is sticky and can be seen on the walls of all exhaust pipes and chimneys. It is formed as a by-product as a result of incomplete combustion of hydrocarbon fuel. Soot gives luminosity to the flames for example yellow flickering glow of a candlelight, this phenomenon has triggered fascination to some of the greatest minds in the past[5]. But soot is not considered to be a good by-product in modern science and technology. Emitted soot has serious implications on human health, environment and climate change. Health implications due to soot is dated back to Aristotle, when he suspected the abortions were caused by “the smell of the smouldering wick of a candle” [6]. The hazards are not just limited to human health; soot is the second most warming agent after CO_2 that is responsible for global warming [5]. Soot also has its fair share in diminishing the agricultural crops due to the inhibition of light and its effects on livestock.

One of the best ways to improve the understanding of soot formation is by conducting experiments in labs with different fuel mixtures. We can study soot formation by altering the fuel mix compositions at the same experimental conditions such as temperature, pressure and strain rate,

and applying decomposition studies and numerical simulation could lead to significant insights. These insights could significantly contribute to the data base of fuel blends.

The objective of our total experimental set-up is to find soot volume fraction by using the line of sight of attenuation (LOSA) an optical diagnostic technique.

2 PROJECT OUTLINE

2.1 OBJECTIVE

As we started the project, the main object was to achieve the 3ms stoke residue time and to keep the cost of the project fairly low, and a less complicated setup and operation.

2.2 TIMELINE OF THE PROJECT FROM AUGUST 2019 TO JANUARY 2020

The project started with a literature review on soot, then followed by a study on the different thermophoretic sampling devices (TSD) that are available. We proceeded to go with an electric TSD design. The secondary research started with finding the right components in the market and at the same time, requesting for quotations from different vendors for the same components. The secondary research was done to find the right linear motor(stator), slider, servo drive, trailing chain cable, power supply, lubricant, USB interface converter, tweezers, set screws, washers, thin hex nuts, gasket sealants and to design a tweezer holder.

Figure 6 Project timeline

In addition, a cost analysis was performed on the component's prices received from multiple vendors. Quotation price of every vendor is compared to other vendors and websites and it was narrowed down to a vendor named *Westburne* in Mississauga. The *Westburne* quote was almost 15% lower to any other vendor in the market across North America for the major components. Then we placed an order with *McMaster-Carr (US)* for washers, setscrews, nuts and gasket. We

shortlisted *Structure Probe, Inc (US)* as vendor for TEM-grids and placed an order with them for tweezers.

After completing the secondary research, we realized that we needed to design a tweezer holder which can fit with the slider that goes into the linear motor. Hence, we designed a tweezer holder and placed an order to machine the bit we needed. We chose to go with aluminum as the material of the tweezer holder to keep the weight of the fabricating bit at the lower end. As there is a penalty with weight, that might decrease the speed of retraction. We needed to also lower the weight. Simultaneously, we searched for the washers, setscrew and the gasket that is needed to make the holder to grip firm to the slider and tweezer. Then things progressed to making of the formal report and presentation. All these events spread were across a span of 6 months as shown in the Figure 6

2.3 LIST OF ITEMS PURCHASED/SELECTED FOR THE PROJECT

S.No	Part Number	Product	Link
1	0150-1285	Liner Motor (stator)	https://shop.LinMot.com/E/product/0150-1285
2	0150-1519	Slider	https://shop.LinMot.com/E/product/0150-1519
3	0150-1771	Servo drive	https://shop.LinMot.com/E/product/0150-1771
4	0150-2187	Trailing chain cable	https://shop.LinMot.com/E/product/0150-2187
5	0150-2480	Power supply	https://shop.LinMot.com/E/product/0150-2480
6	0150-2473	USB converter	https://shop.LinMot.com/E/product/0150-2473
7	SN5AP-XD	Tweezer	https://www.2spi.com/item/sn5ap-xd/
8	92605A043	Set screw	https://www.mcmaster.com/92605a043
9	97725A510	Washer	https://www.mcmaster.com/97725a510
10	90710A037	Thin Hex Nut	https://www.mcmaster.com/90710a037
11	3520C-CF	TEM-Micro grid	https://www.2spi.com/item/3520c-mb/
12	In-house	Tweezer holder	In-house Design
13	7535A12	Gasket Sealant	https://www.mcmaster.com/7535a12
14	0150-1954	Lubricant	https://shop.LinMot.com/E/product/0150-1954

Table 1 List of items used in the project with product website links

2.4 COMPONENTS DESCRIPTION

2.4.1 LINEAR MOTOR (STATOR)

After a significant amount of secondary research, we finally zeroed down on LinMot PS02-23Sx80F-HP-K as the linear motor that we would use for our project mainly because of the high-speed stroke we can achieve using this motor. PS02-23Sx80F-HP-K can achieve a stroke speed of 7.3m/s with force of 67.1N at 32A/72VDC. Important technical data is given in Table 2 as followed. Deciding the motor is a key element for the project by which other components like the electronic drive and power supply were chosen in accordance to the stator specifications.

Figure 7 Linear Motor (Stator): PS02-23Sx80F-HP-K[7]

Max. Stroke Length	720mm	Slider Dia.	12mm
Max. Force at 72VDC	67.1N	Slider Length	130-850mm
Max. Velocity at 72VDC	7.3m/s	Slider Mass	90-700g
Stator Dia.	23mm	Max. Winding Temp	120°C
Stator Mass	245g	IP Code	IP50

Table 2 Technical Data of Linear Motor (stator)[7]

Figure 8 CAD drawings of the linear motor (Stator): PS02-23Sx80F-HP-K[7]

2.4.2 SLIDER

Other important decision to be taken for the project is the length of the sliders and the type of the slider that we need to decide between the slider with and without a bore. As we have no requirement for the bored slider which is twice as expensive compared to non bored slider, we chose to go with slider without the bore.

Figure 9 Heavy duty HP slider [8]

Deciding the length was the other task, as based on the project requirements that we had with us, we needed a stroke length of at least 5.59cm (2.2 inch) above the burner. This is the distance between centre point of the burner up to initial point of the TSS, then clearance needed was 2cm, and the stator has a length of 10.5cm that's the length of slider which is always inside the motor. Keeping the minimum requirements in mind (5.49cm + 2cm + 10.5cm) and adding the scope for future requirements, we chose a length of 230mm (23cm). One end of the slider has an M5 groove for attachment, where we designed an inhouse tweezer holder to fit this slider as show in Figure 19.

Figure 10 CAD drawing of the slider [8]

Length	230mm	Mass	180g
Dia.	12mm	Through bore	no

Table 3 Mechanical Data of slider[8]

2.4.3 SERVO DRIVE E1200

The Servo Drive E1200 is a general-purpose drive that helps in integrating power stage with position resolution for rotary and linear motors. This drive is suitable in achieving our project objective, which is an ultra high-speed stroke with precision across the entire force and velocity range of the LinMot PS02-23Sx80F-HP-K motor. This servo drive works with both 24V/72V power supply but giving the same motor current of 32A. The configuration and parameterization of E1200 is done via the ethernet interface, as this interface is widely used by the industries. Since we needed a USB interface, we also ordered a USB converter; refer to section 2.4.4. Using this drive, we wanted to achieve a linear stroke with a min. residue time of 3ms and similar stroke at 90° angle, by rotating the slider as required. The detailed data of the product can be obtained from the link in Table 1.

Figure 11 Series E1200 Servo drive[9]

Motor supply	24..72VDC	Analog Inputs 0..10V	2
Motor Current	32A	Digital In & outputs	10
Interface	CanOpen, LinRS	Dimensions	40x270x180 mm

Table 4 Servo Drive E1200 data [9]

Figure 12 Illustrative Diagram of Servo drive E1200 with dimensions[9]

2.4.4 USB-RS232 CONVERTER

This convertor helps in providing the galvanically isolate the RS232 interface to a PC or a laptop. Detailed data of the product can be obtained from the link in Table 1.

Figure 13 USB-RS232 interface[10]

2.4.5 TRAILING CHAIN CABLE (2M)

This is a trailing chain cable of two meters that connects linear motor and servo drive E1200, including a K-connector with data as follows. Detailed data of the product can be obtained from the link in Table 1.

Figure 14 Trailing chain cable KS03-W-Fe/K-2[11]

Cable diameter	6.7mm	Cable weight	64 g/m
Min. bend radius stationary	25 mm	Temp. range	-40...+80°C
Min bend radius moving	50 mm	Material according to	UL/CSA 300V

Table 5 Trailing Chain Cable KS03-W-Fe/K-2 data[11]

2.4.6 POWER SUPPLY

The battery was other major decision we needed to consider as we had two variants

Figure 15 Power supply LinMot S01-24/500[12]

available for 500W that works with the stator and the drive we selected. One variant is 72V battery and the other variant was 24V. Keeping the safety considerations in mind, we have chosen the 24V

since the power output for the both is same. These batteries can be directly mounted to the wall or the variant we selected can be snapped to the DNI-rail of 35mm with a diameter of 1 to 2.5 mm.

2.4.7 TEM-MICRO GRIDS

The micro grid is used for collecting the soot from different fuel flames, which is the main objective of our experimental setup. Our project is to facilitate a set-up to collect soot from flames using a micro grid as the collector. We have shorted listed SPI supplies as the vendor for buying the TEM-micro grids. A carbon coated 3mm grid with 200 mesh is selected for our use as shown in Figure 16 below.

Figure 16 3mm carbon coated copper grid with 200 mesh [13]

2.4.8 TWEEZER

A self-locking tweezer was chosen for holding the micro-grid, and this tweezer will hold the micro grid which goes into the tweezer holder that is designed in-house, as explained in 2.4.9. Using a tweezer for holding the micro grid was inspired by the design in the paper of Chu H, Han W, Cao W [1] as depicted in Figure 1.

Figure 17 Self-locking Tweezer to hold TEM-Micro grid [14]

2.4.9 TWEEZER HOLDER

As the slider was having a M5 bore at one end, we needed to design a M5 screw bit that can hold a tweezer which in-turn holds the TEM-micro grid. The available dimension on the slider is M5 bore with a depth of 7.2mm. Hence, we designed a bit with M5 screw of 12mm length that can go inside the slider along with a washer as show in Figure 21 and a nut in Figure 22.

Using an additional hex nut on the threaded shaft of the bit is for giving an additional aid in tightening for the required orientation. Using the hex nut, we can freeze the orientation of tweezer holder angle as required (to make sure the angle is zero to the axis) and use its own threads on shaft for tightening. This design is inspired from motor bikes' rear-view mirror assembly that is commonly used in all motor bikes in India. Threaded M5 screw is 12mm in length, which has enough clearance to use multiple washers and nuts. This design has two shafts with dia. 10mm and 5mm attached concentrically with a total length of 22mm as shown in Figure 18. This is a good design because it can be easily fabricated using one single rod of dia. 10mm and length 22mm on a lathe machine.

On the top and bottom of the 10mm circumference head, there are two M2 tapped holes as shown in the Figure 19. Set screws are passed through it and used to hold the tweezers in its place tightly. We order a liquid gasket as shown in Figure 23, that can be applied on the tweezer to form a thin layer of rubber to absorb vibrations and grip firmly in order to withstand the high-speed stroke action.

The U slit in the tweezer holder as shown in the Figure 19 is used for inserting the tweezer and then making it firm and tight using the set screw and gasket as previously mentioned. This design

included engineering practicality at every step. The detachable tweezers mechanism is adopted so that we can change tweezers as required based on the need or when it is worn out. The liquid gasket sealer was chosen again for convenience.

Figure 19 shows the tweezer holder assembly and all the components that are included for assembly.

Figure 19 Tweezers holder assembly with setscrew, washer and nut.

2.4.10 SET SCREW

M2 threaded set screw with a length of 4mm

Figure 20 CAD drawings of set screws with dimensions[15]

Material	18-8 Stainless steel	Thread size	M2
Hardness	Rockwell B80	Thread pitch	0.4mm
Drive style	Hex	Length	4mm
Spec. Met	DIN 913, ISO 4026	Drive size	0.9mm

Table 6 Set Screw Data [15]

2.4.11 METAL SEALING WASHER

The washer to give extra grip to the hex nut and fill the clearance space.

Figure 21 CAD drawings of washers with dimensions [16]

Material	Copper	For Screw Size	M5
Thickness	0.8-1.2mm	OD	10.4mm
Washer Type	flat	ID	5.2mm

Table 7 Metal Sealing Washer Data [16]

2.4.12 THIN HEX NUT

This is used for aligning the orientation of tweezers holder with zero axis or as required as previously discussed in 2.4.9.

Figure 22 CAD drawings of thin hex nut with dimesions [17]

Material	18-8 Stainless steel	Thread Size	M5
Nut Type	Hex	Thread Pitch	0.8mm
Width	8mm	Thread Spacing	Coarse
Height	2.7mm	Thread Direction	Right Hand
Spec. Met	DIN 439B, ISO 4035	Thread Fit	Class 6H

Table 8 Thin Hex Nut Data[17]

2.4.13 GASKET MAKER SEALANT

The gasket is chosen to act as a seal and also as a vibration absorbent between the tweezer and the tweezer holder.

Figure 23 Gasket Maker Sealant, Permatex 800022, 3 oz. Tub [18]

Manufacturer	Permatex	Temp. Range	-65° to 400
Model No	80022	Begins to harden	60min
Color	Blue	Full strength in	24hrs
Clarity	Clear	Max. gap size filled	0.25"

Table 9 Gasket Maker Sealant Data[18]

2.4.14 LUBRICANT OF STATOR & SLIDER

The synthetic smooth-running grease for effective wear and corrosion protection.

Figure 24 Lubricant LU02-50[19]

2.5 VENDOR & COST ANALYSIS

The vendor analysis was crucial for this project as the components we were buying were for industrial use only and the cost varied across the suppliers. After rigorous communication, we shortlisted two top contenders to choose from; first was Westburne (Mississauga), an authorized dealer in Ontario, Canada for LinMot products. Second one was the MotionUSA, who were prompt in replies and provided good customer care but quoted significantly more compared to Westburne. As price was a key factor and Westburne offered a modest quote, we chose them for our academic project. Other fueling factors included the technical support offered by the Motion Specialist of Westburne, who addressed all our concerns regarding the products we ordered. After all of the required changes and updates, we placed an order with Westburne to LinMot on December 9th, 2019. Then we placed an order with McMaster-Carr (US) for washers, setscrews, nuts and a gasket. We shortlisted Structure Probe, Inc (US) as a vendor for TEM-grids and placed an order with them for tweezers.

3 CONCLUSION AND RECOMMENDATIONS

The design of the thermophoretic sampling system is completed and we placed an order for the required components. Integrating all the components featured in Figure 25 will make the design ready.

Figure 25 Thermophoretic sampling system all components

1. Linear motor(stator); 2. Slider; 3. Servo drive; 4. Trailing chain cable; 5. Power supply; 6. USB interface converter; 7. Tweezer, 8. Set screw; 9. Washers; 10. Thin hex nut; 11. Micro-grid; 12. Tweezer holder;

Using the instruction given in 2.4.9 complete the assembly of the design with stator, slider and tweezer holder, it should resemble to Figure 26. Fully assembled thermophoretic sampling system (TSS) we designed should resemble to Figure 27

Figure 26 Assembled design of tweezer holder, slider and stator

Figure 27 Fully assembled design of thermophoretic sampling system (TSS)

3.1 FUTURE SCOPE OF THE PROJECT

The current scope of the project is only the design of the system. The further scope would be integrating the system and defining the sequence action that must be performed by the linear motor. All the required software and handbooks for the setup is provided on the LinMot website. All the links are placed in Table 1 in the respective row of the product for reference.

3.2 RECOMMENDATIONS FOR SEQUENCING

1. Stroke sequence is done in a three-phase motion. The first phase would be slowly reaching to the point just before the flames, namely the stroke point, then a fast stroke to the centre point of the flames with retractions as per the required residue time (3ms, 30ms, 100ms) to the stroke point. Then the final phase is a slow retraction and a cool down to the initial point. Progressing in three phases would help in getting the required least residue time to 3ms, as the path that has to be travelled in ultra-high speed is reduced to just the radius of the burner.
2. The similar stroke is to be sequenced with an initial 90° rotation and follow the same sequence as in point 1.

Caution: As this linear motor is basically used for repetitive motions, the cool down sequence needs to be initiated and the end of the third phase so that the stroke won't be repeated.

APPENDIX

Following was the in initial design iteration of the tweezer holder, but we did not go a head with this design as it is difficult to manufacture this by just using a lathe. This design led us to a final design that we came up with and discussed in the report. Final design in Figure 19 is easy to fabricate using just one piece of aluminum rod of dia. 10mm as this is a design with two concentric shafts unlike the design in Figure 28.

Figure 28 First design iteration of tweezer holder not easy to be fabricate

First design iteration of tweezer holder drawing and measurements, other noticeable change here is to use M1.6 for set screw, in the final design it is changed to M2.

Figure 29 Drawing of first design iteration of a tweezer holder.

BIBLIOGRAPHY

- [1] H. Chu, W. Han, W. Cao, M. Gu, and G. Xu, “Effect of methane addition to ethylene on the morphology and size distribution of soot in a laminar co-flow diffusion flame,” *Energy*, vol. 166, pp. 392–400, Jan. 2019, doi: 10.1016/j.energy.2018.10.093.
- [2] M. Leschowski, T. Dreier, and C. Schulz, “An automated thermophoretic soot sampling device for laboratory-scale high-pressure flames,” *Review of Scientific Instruments*, vol. 85, no. 4, Apr. 2014, doi: 10.1063/1.4868970.
- [3] A. M. Vargas and Ö. L. Gülder, “A multi-probe thermophoretic soot sampling system for high-pressure diffusion flames,” *Review of Scientific Instruments*, vol. 87, no. 5, May 2016, doi: 10.1063/1.4947509.
- [4] M. Altenhoff, C. Teige, M. Storch, and S. Will, “Novel electric thermophoretic sampling device with highly repeatable characteristics,” *Review of Scientific Instruments*, vol. 87, no. 12, Dec. 2016, doi: 10.1063/1.4971988.
- [5] C. R. Shaddix and T. C. Williams, *Soot: Giver and taker of light*. American Scientist, 2007.
- [6] Aristotle, *The works of Aristotle*. Penn State Electronic Classics Series Publication, 2005.
- [7] Liner Motor (stator), “<https://shop.linmot.com/E/product/0150-1285>.”
- [8] Slider, “<https://shop.linmot.com/E/product/0150-1519>.”
- [9] Servo drive, “<https://shop.linmot.com/E/product/0150-1771>.”
- [10] USB converter, “<https://shop.linmot.com/E/product/0150-2473>.”
- [11] Trailing chain cable, “<https://shop.linmot.com/E/product/0150-2187>.”
- [12] Power supply, “<https://shop.linmot.com/E/product/0150-2480>.”
- [13] Mesh, “<https://www.2spi.com/item/3520c-mb/>.”
- [14] Tweezers, “<https://www.2spi.com/item/sn5ap-xd/>.”
- [15] Set screw, “<https://www.mcmaster.com/92605a043>.”
- [16] Washer, “<https://www.mcmaster.com/97725a510>.”
- [17] Thin Hex Nut, “<https://www.mcmaster.com/90710a037>.”
- [18] Gasket Maker Sealant, “<https://www.mcmaster.com/7535a12>.”
- [19] Lubricant, “<https://shop.linmot.com/E/product/0150-1954>.”