DESIGN AND IMPLEMENTATION OF A CIGARETTE SMOKING MACHINE

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ABSTRACT

The objective of this project is to design and build a cigarette smoking machine, as well as, to develop a hardware and software interface between the smoking machine and human lung cast. The previous prototype did not meet any customer requirements, which included imitating the human breathing process, an automated flameless non-contact ignition, and the ability to control the airflow through the machine. The machine will be used for a particle deposition study, which is supported by Grant RSG-05-0221-01-CNE from the American Cancer Society. After the machine is designed and fabricated, the purpose of the machine is to be capable of measuring this deposition. A Graphical User Interface (GUI) will be created to control the flow path and monitor the needed sensors. Analysis of the collected data should show that the deposition of cigarette particles in the human lung is in correlation with the thesis study performed by Jackie Russo.

INTRODUCTION

The cigarette industry today is a multibillion dollar business that attracts people using advertisements to lure customers to purchase their product. People who habitually smoke are shown to have a higher risk of developing health problems such as lung cancer and heart disease. Smoke travels down the smoker’s larynx to the lungs where the cigarette particles may have a chance to settle. The purpose of this project is to simulate the behavior of smoke in the lungs of a smoker, and non smoker, to observe the resulting particle deposition. With those results, it should be capable to understand if particle deposition in the lungs is directly proportional to lung cancer.

The project began in the summer of 2007 when Jackie Russo, a Mechanical Engineering student, performed her thesis concerning the effect of cigarette smoke in an adult female’s lungs. This project picked up where she left off in the fall of 2007. The purpose for this Senior Design project is to build a machine and lung cast to be used to help determine the actual smoke particle deposition.

The project consists of two teams, the machine team and the lung team. The machine team will focus primarily on the physical designing and implementation of the system. The system is supposed to simulate an accurate representation of human respiration excluding the lungs. The lung team will focus primarily on the construction of a set of lung casts. Using provided models of the lung airways created by Jackie Russo and Jessica Weisman, the smoker and non smoker lung casts will be designed. The models are then to be created using today’s prototyping...
techniques. The models are to be linked to the machine’s flow path for the use of testing.

Over the period of twenty weeks, both teams will design, simulate, and construct a mechanism that will simulate a person smoking a cigarette with the smoke depositing in the lung cast. Five research cigarettes (3R4F) will be smoked simultaneously or individually with a flameless ignition. The LabVIEW interface will be designed to regulate the puff profile, along with controlling the flow path throughout the machine during each test.

**DESIGN PROCESS**

**Customer Requirements**

Both the machine and lung teams have very specific requirements. The lung team has requirements which are specified from the customer, while the majority of the machine team’s are from the ISO 3308:4000E document. This ISO standard is a very detailed compilation of rules that all smoking machines adhere to.

**Machine Requirements**

The machine team requirements are specified from both the sponsor and the ISO document. Specifications from the sponsor include the entire machine being sealed from the exterior and viewable at all angles, an effective way to properly vent the smoke, a modular test section in the machine, LabVIEW interface to control the puff profile, and a very easy way to assemble and disassemble parts of the machine if needed. Last, the sponsor requested the machine be as automated as possible so that little human interaction is needed. Specifications for the ISO document are detailed in three different sections; the ignition, the cigarette length detection, and the flow characteristics. The cigarette ignition must be flameless, while not having any physical contact with the cigarette. The cigarette length detection needs to be repeatable with integration into the LabVIEW interface, and should also not have any contact with the cigarette. The flow characteristics of the machine include path symmetry to the humidity chamber, pressure drop across cigarette, and a puff profile. The puff profile is required to have an adaptable shape and frequency indicated by the user, and puff duration of 2.00 +/- 0.02 seconds.

**Lung Cast Requirements**

The lung cast requirements are specified only from the sponsor since this will be one of the first smoking machines to incorporate a lung cast into the smoke path. The requirements include an outer shell of the given lung path models, a mouth piece that matches the Computational Fluid Dynamics (CFD) analysis, and a lung cast that is reusable, cleanable, with the ability to be removed from the machine without difficulty. The design and material must have a rigid structural integrity, repeatable mounting location, and maintain sealed from the rest of the machine.

**Design Specifications**

The design specifications for the cigarette smoking machine branch from the sponsor as well as from the ISO 3308:4000E requirements that were stated. Other specifications are given by the RIT Environmental Health and Safety (EHS) and have to be met in order to allow the machine to be operated indoors. The main requirements given by EHS dealt with the flameless ignition and sealing of the machine’s enclosure.

**Humidification Chamber (provided by the customer)**

- Clear acrylic 4” diameter tube, 3.5” long
- Each end has to be removable. Suggest a clasp on 4 sides to ensure tight seal.
- O-ring between the end pieces and the caps to ensure tight seal.
- Mainstream smoke shall be heated to 37°C and humidified to 90% or greater

**ISO standards**

- **Cigarette pressure drop**
  - The whole flow path between the butt end of the cigarette and the suction mechanism shall offer the least possible resistance, and its pressured drop shall not exceed 300Pa.
    - A pneumatic circuit when it is traversed by and airflow under steady conditions in which the measured volumetric flow, under standard conditions, at the output end is **17.5 ml/s**.

- **Puff duration**
  - The standard puff duration shall be **(2.00 +/- 0.02) seconds**
    - Interval of time during which the port is connected to the suction mechanism

- **Puff volume (needs to be variable 35-60ml)**
  - The standard puff volume measured in series with a pressure drop shall be **(35.0 +/-0.3 )ml**.
  - In one puff duration not less than 95% of the puff volume shall leave the butt end of the cigarette

- **Puff frequency (needs to be variable <60 seconds)**
  - The standard puff frequency shall be one puff every **(60 +/- 0.5) seconds** measured over 10 consecutive puffs.
    - Number of puffs in a given time

- **Puff profile**
  - It shall be bell-shaped with a maximum **between 0.8 and 1.2 seconds** from the start of the puff. The increasing and decreasing parts

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of the profile shall not have more than one point of inflection each. The maximum flow rate shall be between 25 ml/s and 30 ml/s. At no point shall the direction of flow be reversed

- Flow rate measured directly behind the butt end of a cigarette and depicted graphically as a function of time.

- Puff number count
  - Each individual puff shall be counted and recorded and the puff number rounded off to the nearest one-tenth of a puff based on the puff duration
  - The puff number is the puffs necessary to smoke a cigarette to the specified butt length

- Cigarette seal and holder
  - The design of the standard cigarette holder is such that it shall cover 9.0mm, with a range of 8.0mm to 9.5mm, from the butt end of a cigarette, and shall be impermeable to smoke components and to air.
  - Cigarette seals which meet requirements were provided to the team by Dr. Mike Oldham. A cigarette holder was given so that it can be reproduced.
  - The axis of the holder shall be 0 to +5° of the horizontal and the holder shall ensure that the cigarette is held within +/-5° of the holder axis.
  - Manufacturing tolerance for the individual components of the cigarette holder can not result in an uneven tolerance about the specified 9mm insertion depth.

- Cigarette position
  - The cigarette holders shall be arranged so that no cigarette influences the burning of any other cigarette. The butt end should be in contact with the washer when inserted.

- Ashtray position
  - The ashtray shall be placed in a horizontal plane between 20 mm and 60 mm below the plane of the axes of the cigarettes.

- Butt length
  - Smoked until the cigarette is 23 mm.
  - See ISO 3308 for additional details

The machine must be able to hold and load up to five cigarettes at the beginning of each test.

The machine must be capable of smoking the five cigarettes simultaneously (in parallel), or smoke each individually (in series) with no effects from others.

The assembly and disassembly of all components must be simple and trouble free since cleaning and replacing parts will be very common during operation.

Design should allow interchanging of three distinct and separate legs or test sections.

- Leg 1 - Pall Stainless Steel 47mm for Chemical Analysis
- Leg 2 – Mini-MOUDI M110 Impactor for Particle Size Filtering (followed in series with Pall Stainless Steel Filter)
- Leg 3 - Lung Cast for Particle Deposition for Correlation with Thesis Results (followed in series with Pall Stainless Steel Filter)
  1. Each bronchi connected to central plenum

Each of the legs will then be connected in series to a condenser and additional filters. These components will be added to extend the life of the flow controller and vacuum pump which complete the flow path for smoke.

**Background Research (Lung Team)**

Research was done on basic human lung anatomy. From there, the team looked into various ways of producing a part or sample of the replication of the human lung up to the fourth generation. Information was sought on different processes, but due to the complex nature, it was decided to go with rapid prototyping rather than modeling and casting the lung.

**Background Research (Machine Team)**

The background research for the machine team consisted of getting familiar with the ISO specification and beginning to develop concepts which would be implemented to adhere to it. Due to the customer’s need of having the machine be as automated as possible, the machine team set their goals high to accomplish a fully automatic system. The majority of the research was spent on items which were determined to be high risk. Some focused areas of research were to address the potential problems of a flameless ignition system, automatic length detection system, and the ability for a user controllable puff profile.

Another area of research which was carried out by the machine team was health and safety. Fire safety and health codes were examined to ensure the machine enclosure could pass inspection without problems. Due to the hazards of smoke, the entire machine would have to be leak-proof. Also the machine was required to withstand and contain a flare up without a fire occurring to rest of the machine. The enclosure of the machine would need to be vented to a fume hood to allow the escape of all smoke contained inside the machine.
The last portion of research which was undertaken by the machine team involved the analysis of cigarette smoking machines which were available to consumers. This was important to receive ideas in how some of the tougher problems that would be faced could be solved and proved to be a great method of brainstorming.

**Concept Development (Lung Team)**

The approach the lung team took was a rapid prototype. Two models consisting of the airways of the lung cast for the smoker and non-smoker were provided from Jackie’s thesis. The mouthpiece for the non-smoker is shaped like a rectangle while the mouthpiece for the smoker is shaped like a circle. It will be difficult to seal the non-smokers mouth since the tubing is circular, as a result the mouthpiece will be modified into an oval shape for an easy connection to the machine.

Rapid prototyping companies, including RIT, were researched for the price and the lead time to be able to prepare both models.

**Concept Development (Machine Team)**

The machine team developed an entire flow path in concept development which contained solutions to all major customer needs and the ability for advancement.

In the initial front end concept, above, contained the use of a linear actuator to control the movement of lighters found in an automobile. Making use of normally closed solenoid control valves, the flow path of smoke could be controlled though each of the cigarettes individually or all at once. Another feature to the concept was making use of the provided humidification chamber, which would heat and humidify the smoke to simulate the conditions inside a human’s mouth. Humidification would occur as the smoke traveled through presoaked sponges which obstructed the flow path.

The concepts developed for the end assembly had to take into account the ability to control and monitor the flow at each of the seventeen lung cast exits. This required the installation of seventeen variable flow controllers. The seventeen exits would then be brought together making use of a manifold-typed plenum having one exit. The exit of this plenum would contain a condenser and catch all filters which would remove the added humidity and remaining smoke deposition. Either of these could drastically cut into the expected lifetime of the vacuum pump, which completed the entire system.

The machine team chose to make the skeleton of the machine enclosure out of T-Slotted Extruded Aluminum. Clear cast acrylic sheets would be slid into place to allow for a tight seal and great viewing at any angle.

After consultation from the team’s advisors some of the machine team’s concepts were refined and changed. The major changes in concept were done to reduce costs, to remove restrictions in the overall flow path, and improve on space utilization. A suggested change in the front end assembly consisted of removing the plenum following the cigarette holder and to directly vent the cigarettes into the humidification chamber. There were multiple benefits to this change. First, it reduced the overall length of the system on the upper shelf and saved space. Second, there was concern that the flow would not be consistent between each of the cigarettes entering and exiting the plenum. Last, this change allowed for the ability to vent and purge the entire system with fresh air in between each puff from directly behind the cigarette.

The second major change, which occurred after consultation from the team’s sponsor and advisors, was to remove the seventeen flow controllers after the lung cast exits and replace them with one single flow controller placed just after the catch all filters and just before the vacuum pump. Again, this design change had multiple benefits. First, the cost of each of the flow controllers was in upwards of $1900. The controllers had to be highly accurate and responsive, as well as, withstand the effects of humidity and cigarette smoke without failure. Second, an expert in the field suggested that putting the controller in the path of smoke without a 100% filter prior would not be recommended. The accuracy of the meter would significantly fall after just a single puff. By moving the flow controller to the end of the system, it was ensured that no smoke deposition would come in contact and ensure accuracy throughout the test’s entirety.
DESIGN IMPLEMENTATION

The implementation of the cigarette smoking machine involved the construction of the smoking machine. A LabVIEW based computer interface was also built to allow the machine to run tests automatically. The lung cast implementation was an important part of the build because without it, there would be little reasoning for the existence of the entire machine.

Machine Implementation

The machine design underwent a slight redesign after receiving the table for building. The previous square design was thrown away and replaced by a longer and narrower design which would allow better space efficiency. The extruded aluminum enclosure was assembled to size and fastened to the table before the cast acrylic sheets were inserted to complete the outer enclosure.

The parts needed for assemblies of the front assembly were machined with little difficulty or obstacles encountered. The team decided to build the entire front assembly with the shelf removed to allow easy access for mounting components. The shelf was easily inserted back into the machine after all the required constructing was complete.

It was at this point that the machine team realized that the humidification chamber would not fit in the space provided. After further analysis, a member of the design team determined that the current humidification chamber was extremely oversized. After essential changes were made to this particular piece, the designed machine layout was able to yield enough space to allow the fitting of all machine components.

Specific components of the flow path were mounted and added to the machine so that the machine wiring could begin. Some of these components included the automotive lighters used for non-contact ignition and Clippard solenoid valves, which would be used to control the flow path of smoke in the machine. And the rest were added upon receipt of the team, such as photoelectric sensors.

A couple of problems occurred during machine construction that required for immediate action, but did not hinder the overall progress of the build. One of the problems which transpired was the incorrect part being delivered. Therefore, due to circumstances beyond our control, the machine will be unable to control the flow and monitor it. This also does not allow the user to input a specific flow curve for testing. The second problem rose about after a machining error on the part of one of the members. The part design had to be slightly optimized, however, the overall function should not be affected in any way.

After all wiring was completed to each of the machine’s components the networking between the machine and Data Acquisition (DAQ) began. Through the use of a Graphical User Interface (GUI), the machine was capable of running with nearly no interference and full automation during testing.

The last component which was connected to the machine’s flow path was the lung cast and plenum. The plenum was necessary for combining the seventeen lung cast exits into a centrally located exit. This addition completed the build of the machine and almost all requirements for the project.

Software Implementation

Programmer’s Guide

- **Design Overview and State Table**
- **State Transition**
  - State Diagram
  - State Description

Taking into account the nature of the smoking machine and the process flow, the main approach in designing the system was targeted towards utilizing a finite state machine. Each state is responsible for a certain portion of the system flow by recording the sensor data and adjusting appropriate control outputs. Figure 1 represents the state machine implemented for this project and the flow path.

![State Transition Diagram](image)

**Figure 1. State Transition Diagram**

**Idle State**

At machine power on, the system goes to idle state, during which it is setting the machine up for a new experiment, and purges the flow path while waiting. At this moment the airflow is set to go through the bypass pipe, all air valves are opened, and all cigarette valves are closed. This is where the type of the experiment is chosen, and cigarettes are inserted. If there are no cigarettes inserted, or one of the doors is opened, the system will not start. After beginning, the machine goes to the next state, depending on the type of experiment chosen (i.e. Light Cigarette Simultaneous or Light Cigarette Continuous).
LightCigarette Simultaneous State
During this state the system lights up all available cigarettes simultaneously, which follows a 5-step process:

1. Start the corresponding cigarette lighters and wait until they warm up
2. Extend the actuator
3. Close all air valves and open the cigarette valves associated with the cigarettes being lit up. Wait time until the cigarettes are lit.
4. Contract the actuator
5. Switch the bypass pipe to the lung cast and go to the SmokeCigarette Simultaneous State.

Other actions associated with this state include: start collecting data for storing it into a file, based on the sampling rate specified under edit, and disabling all buttons except the stop button to prevent parameter changes during the execution of the experiment.

SmokeCigarette Simultaneous State
During this state the system smokes the cigarettes based on the puff profile specified in the edit section using an array of flow output corresponding to time. This is also when puff counts are taken and recorded. The system smokes the cigarettes until the user indicates that one of the cigarettes has reached the desired smoking butt length. This marks the end of the experiment, the experiment timer stops, and the system goes into the Exit state.

LightCigarette Continuous State
During this state the system lights up the first available cigarette, following a 5-step process:

6. Start the corresponding cigarette lighter and wait until it warms up
7. Extend the actuator
8. Close all air and cigarette valves and open the cigarette valve associated with the cigarette being lit up. Wait time until the cigarette are lit.
9. Contract the actuator
10. Switch the bypass pipe to the lung cast and go to the SmokeCigarette Continuous State.

Other actions associated with this state include: start collecting data for storing it into a file, based on the sampling rate specified under edit, and disabling all buttons except the stop button to prevent parameter changes during the execution of the experiment.

SmokeCigarette Continuous State
During this state the system smokes the cigarette based on the puff profile specified in the edit section using an array of flow output corresponding to time. This is also when puff counts are taken and recorded. The system smokes the cigarette until the user indicates that the cigarette has reached the desired smoking butt length. If there are other cigarettes available the system updates the next cigarette to be lit and goes back to the LightCigarette Continuous state.

If there aren’t any cigarettes left, the experiment ends here and timer stops. The system then goes to the Exit state.

Exit State
During this state the system is done with an experiment and gives the researcher the opportunity to save the acquired data into an Excel file, by activating the Save button. Also all cigarette valves are closed, and all air valves are opened, as well as the airflow is directed through the bypass pipe.

Lung Cast Implementation
The lung cast is to be connected to the machine assembly at the mouth. The original idea was to have small pressure sensors at certain points along the lung cast to measure the pressure drop, however small pressure sensors are extremely difficult find and design around with any confidence. The pressure drop which would be needed for measurement would need to have a high accuracy in a very low pressure application. A new design without positions for pressure sensors was created, and the old design was scrapped for future considerations. (See “Recommendations for Future Work”)

The material that was initially used to mold the lungs was ceramic. After rapid prototyping a section and pouring water through it, it was observed that the material was weak and was likely to be water soluble. The water began to dissolve the ceramic and the lung cast dissolved. Since the water so readily broke the bonds in the ceramic prototype, it is likely that the methanol would have a much more volatile reaction.

Due to this obstacle outside vendors were considered for implementation. ProtoCAM, a company in Pennsylvania, who later received our contract, changed the rapid prototype method used by others and instead used a stereolithography technique. This technique produced a much greater quality of product. In addition to this, the material used was capable of being transparent.

ProtoCAM shipped a sample of the lung cast which was created using their stereolithography machine. It was important that the cast material would hold up to the chemicals that would be used to clean it. So the sample was soaked in methanol at several time intervals, 30 seconds, 10 minutes, and 3 hours. The solution from the soaking was then evaluated using a GC/MS machine. The machine was used with the aid of Professor Todd Pagano. The results from these tests are as follows. This chart is displaying a 30 second soak versus pure methanol.
The above graphic has the results for a 30 second soak, a 10 minute soak, the 3 hour soak and the pure methanol superimposed.

From these results the material was determined to be acceptable in a methanol wash environment. From this, a full smoking cast was given for purchase to ProtoCAM. A picture of the file and end product is shown:

This cast was installed in the machine. The nonsmoking model is designed and awaiting a quote. This nonsmoker model has one main design change which makes it different than the smoker model. The mouth inlet is a 2mm by 18 mm oval, and the exhaust from the tubing is a ¼”. Design considerations and testing were needed for this geometrical anomaly, however, a final model was created. The nonsmoker mouth change is shown.

DESIGN VALIDATION

In order to create a fluid flow that was concurrent with the inlet conditions for a non smoker, it was necessary to create a geometry change. The geometry change refers to going from a ¼ inch diameter tube on one end to a 2mm by 18mm oval inlet to the mouth at the other. A picture of the described change is shown below:

With this alteration, there was a reduction of area between the shapes. As this area decreased, the speed of particles exiting the model increased. The inlet conditions being 15ml/s gives you a 1.88493 m/s at our flow conditions of $\rho_{air} = 1.15727 \text{ kg/m}^3$ and an area of $7.917 \times 10^{-6} \text{ m}^2$.

With the inlet and fluid properties held constant the exiting velocity was analyzed by varying the lengths of the model. The tested lengths were 1, 1.5, 2, 2.5, 4, and 5 inches, the results compared the exiting velocity to that of the inlet. The graph below shows the results from the testing.

The x-axis represents the length in inches and the y-axis is the exiting velocity in m/s.
In order to find and compute the numbers, it was necessary for the model to be drawn in Pro-E, and then meshed in Gambit. The computational fluid dynamics was performed using Fluent. The inlet conditions for each length were held constant with the only variable being the length of the model. The exiting velocity gradient for the 2 inch model appears below.

From this data it becomes apparent that the 2 inch model is an ideal case, and was the reasoning behind being incorporated into the non-smoking model, as seen below:

**TEST RESULTS**

This design project was particularly unique in the fact that there was no real testing that determined the project’s completion. The true test for the overall design validation was ensuring the machine functioned properly. The design team made multiple efforts in testing individual components of the system and its operation throughout the build process to guarantee that no problems would occur in the end.

The testing of the automatic, non-contact, flameless ignition system went as planned. The initial test had shown that our setup left the cigarette too far away from the lighter and resulted in no ignition. Using some of the adjustability built into the mounting brackets, a slight correction was made to move the cigarette closer. The team is proud to say the ignition system has now had a 100% ignition rate since this change for over 50 cigarettes.

Due to the effects of the smoke, initial testing was needed to be performed outdoors. The sealing of the machine enclosure was a vital test for the team before testing indoors. A visual inspection was performed and passed during the initial outdoor test. Knowing the machine would have a ventilation fan attached while running indoors, the team was satisfied with the results.

The testing of the machine’s humidification chamber could not be performed. Due to the sizing change of the chamber, the correct heating pads could not be purchased in time for the final build. Also, a change in the thermocouple probe will take place to remove any inaccuracies which may occur from oxidation from the humidity. A calibration of the humidity sensor was done before installing and testing to be sure it functioned correctly.

A test of the machine’s flow and test cycle was the last test performed by the team. Since each of the solenoid valves were tested previously for proper functioning, the test was done by verifying the GUI powered the correct relays at the correct times in the experimental run. A mix up between the test leg valves and the bypass leg valves was found and easily fixed. The testing of the machine-software interface was passed and completed. The completion and passing of this test was the end of all the testing.

**CONCLUSION**

The overall design of the smoking machine and lung cast proved to be a great experience for all of the team members. The team was able to learn and experience firsthand the many components which make up a system. Many steps were necessary for implementation of each of the systems pieces, machine, wiring, software, and lung cast. Good communication and hard work were the key factors which allowed for a successful design by the team.

The team, Dr. Risa Robinson, and Dr. Kathleen Lamkin-Kennard had the pleasure of giving a working demonstration of the machine to multiple local news stations. Reporters were present at the time who asked members of the team questions on how the machine worked. This proved to be very rewarding and gratifying for all of the hard work which went into the project over the twenty two week period.

**RECOMMENDATION FOR FUTURE WORK**

For the lung implementation:

- Include pressure sensors in the lung cast model in order to get data for comparison for computational models.
- Comparison between the lungs of a teenager and that of an adult, in other words, a size comparison.
For the machine:

- Design and implement a system to periodically remove the ash to simulate smoking more realistically.
- Implement flow controller with flow capacity for smoking all five cigarettes together.
- Design and implement a pressure scanner assembly which could allow adjustment of pressures or flows out of each of the exits of the lung cast.

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