Motivation for Mass Flow Calibration

Abstract: Electric propulsion is the conversion of electrical energy to kinetic energy of a gas to generate thrust. These devices generate high efficiencies by expelling a small amount of propellant at very rapid speeds. The price paid for such high efficiencies is low thrust. Measuring the thrust produced by these devices requires highly sensitive measuring techniques, and acute accuracy in the delivery of propellant to the thruster. It is the duty of our lab facility to ensure that the gas delivered to the thruster is the gas commanded by the operator. With the improvements made to the lab by the hands of yours truly, we can now calibrate not only the mass flow controllers, but also the entire propellant delivery system.

Principles of Electric Propulsion

"All propulsion is potatoes." My thermodynamics professor once told me. "The goal of any propulsion system is to throw potatoes away from you, so that by the conservation of linear momentum, you will be propelled in the opposite direction." I've always loved that definition, partly because of the way it sounds out loud, but mostly because it succinctly captures the essence of all propulsion devices.

Chemical rockets, jet engines, hall-effect thrusters with magnetic shielding, hair dryers… are all devices that convert some form of energy into the kinetic energy of potatoes. In the case of chemical rockets, its burden is to convert chemical energy that is stored in the propellants (fuel and oxidizer) into kinetic energy of the propellants out a nozzle. Jet engines serve the exact same purpose, the only difference being the manner by which these machines *condition* the fuel and oxidizer for the release of energy stored in chemical bonds. Rockets use pumps, jet engines use tiny spinning wings. Chemical propulsion is limited however, by the amount of energy one can store in the chemical bonds.

This is where my area of research steps in. Electric propulsion is the conversion of *electrical* energy into the kinetic energy of a gas (potatoes). All matter is composed of atoms, and atoms are composed of an entire zoo of particles; I will focus on just 2: electrons and protons. Electrons and protons have associated with them something called an electrical charge. Electrons have *negative charge* and protons have *positive charge*. This really means nothing. I might as well have said electrons are red potatoes and protons are blue potatoes. For reasons that are under no obligation to make sense to us: red potatoes HATE red potatoes but LOVE blue, and blue potatoes HATE blue potatoes, but love red. This is synonymous with the saying, "Like charges repel, opposite charges attract." These particles attract and repel each other with a force called Electrostatic Force, which can be compared to the Gravitational Force. What should make you uncomfortable is that the electrostatic force is 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000 times stronger than gravity. Electric propulsion devices use electrical energy to establish an environment such that this tremendous force is allowed to act on ionized gases and send them screaming out the back at speeds on the order of tens of kilometers per second.

The advantage of electric propulsion is that, as we increase the exit velocity, we increase the efficiency. The way we increase the exit velocity is by increasing the electrical energy sent to the thruster. It just so happens that there is no limit to the electrical energy we can deliver to the thruster, so electric propulsion devices have tremendous efficiencies. But what is the price we pay for such high efficiencies? Thrust. The thrusters in our lab produce forces that will push no harder on your hand than the weight of a piece of paper. However, in the vacuum of space in the absence of drag, a small constant force will produce a constant acceleration, and over time this constant acceleration will result in tremendous velocities.

The reason the thrust is so low is because, although the exit velocities are so large, the exhaust plume lacks momentum. Momentum is how much stuff you throw out times how fast. A passenger airplane jet engine heaves large amounts of mass at a relatively slow velocity to achieve thrust, but our thrusters send a very small number of atoms out the thruster at enormous velocities. We are able to generate considerable amounts of thrust while maintaining such high efficiencies by gently burping a few atoms at a time at 0.01% the speed of light.

Motivation for Mass Flow Calibration

One can imagine, when determining the weight of a piece of paper, the sensitivity by which you measure that weight is very important. In the same way, when we have a thruster in our lab and we wish to determine its thrust, we MUST be able to ACCURATELY report the mass flowrate delivered to the thruster. We have instruments that can determine how fast the exhaust gases are flying, but there is no such instrument to measure how much gas is being thrown out. We need both to compute the change in linear momentum, and thus the thrust. It is specifically this question that my research addresses: **How can we ensure that the mass flowrate *commanded* by the operator is the mass flowrate delivered to the thruster?**

Electric propulsion devices are used in space and thus tested in vacuum chambers to simulate space environment. Previous iterations of the lab have used analog mass flow controllers that are 10 meters away from the thruster, *outside the vacuum chamber*, to set the flowrate to be delivered. Analog means that they increase the flowrate through the controller as the voltage delivered to the controller increases. So, if we want a large flowrate, we send a large voltage to the controller. For a small flowrate we send a small voltage. The problem was that the mass flow controllers were 30 meters away from the power supply, and thus a voltage drop across the wire to the thruster was inevitable. So, before one can discuss leaks, uncertainties, bends, etc. There is already a loss of flowrate simply due to the voltage drop along the wire. To compensate for this, we perform something that was very mysterious to me for a long time. We calibrate.

Calibrating is correlating the readings of an instrument with those of a "standard" in order to check the instrument's accuracy. In this context, the instrument whose accuracy we are concerned with is the mass flow controller, and the "standard" we are comparing to is the mass flowrate commanded by the operator. When I say 10 milligrams per second, I want to see 10 milligrams per second from the mass flow controller. So, what we do is we hook up a device to measure the flowrate immediately downstream of the controller; I command 10 and measure the flowrate. Because of the voltage drop in the line, by the time the signal reaches the controller, it no longer carries the weight to generate a mass flow of 10, but instead carries the weight of something corresponding to a mass flowrate of 9. Thus, when I measure the flowrate, I measure 9. If we measure this discrepancy across a series of points when obtain what is called a calibration curve, which is the relationship between the commanded value from the operator, and the measured value from the mass flow controller. In the example I've contrived, a point on the calibration curve would consist of a commanded value of 10, and a measured value of 9. If I find that for any commanded flowrate only 90% makes it to the thruster, then to obtain a measured flowrate of 10, I should command 10/0.9 = 11.1. Thus, after the voltage drop the voltage delivered to the controller carries the weight corresponding to a mass flowrate of 0.9*11.1 = 10. Therefore, to summarize the purpose of the calibration curve: the calibration curve provides us with the *conditioned* commanded value corresponding to any desired measured value, despite any losses.

The lab made some money and our technology improved. As of summer 2017 we are equipped with digital mass flow controllers that eliminate the losses due to voltage drops. Instead of operating on an analog voltage, they receive a string of 1's and 0's that are interpreted as a commanded mass flow rate. Of course, it is still voltage-based. A binary signal is sequence of voltage pulses where the highs correspond to a 1, and the lows correspond to a 0. Even if the wire is incredibly long, with a significant voltage drop, the interpreter (in this case the mass flow controller) will always be able to distinguish a high from a low, and thus the message is transmitted with no loss of information. Well that takes care of that problem.

With the addition of the digital mass flow controllers we were able to focus our attention on another issue. That being the losses in flowrate due to the plumbing that carries the gas from the controllers to the thruster. Thrusters operate on tiny amounts of fuel. If I held the injector 2 inches from your face, you might feel the slightest of breaths from the gas. Any leak in the plumbing is significant and we do our best to eliminate any risk of leaks. We use all Swagelok tubing, joints, fittings, and valves (replacing as needed) and we leak check regularly. Despite our efforts, some gas will always… always escape. Even if our commanded mass flowrate makes it to the controller completely untarnished, the gas still has about 10 meters of tubing, 5 valves, and a dozen joints before it gets to the thruster to decide if it wants to jump ship. Thus, we are in a position now where we a calibration curve would sure be useful.

The issue that I so conveniently glossed over during our first calibration method is that the device we used to measure the flowrate immediately downstream of the mass flow controllers, is just that: it's immediately downstream of the mass flow controllers. It’s actually not a device, but an apparatus: (some of you may have heard it called the calibration bottle). I won’t go into too much detail, but it’s essentially a bottle that we can inflate and measure the change in pressure over time. The change in pressure over time can be related to the mass flowrate, given we know enough information about the gas involved, the volume, and temperature of the bottle, etc. Anyway, this apparatus is outside our vacuum chamber with the mass flow controllers, and thus CANNOT measure the flowrate AT the thruster. What do we do? We buy a $17,000 portable flowmeter that can report very low flowrates with extreme accuracy. This baby is called the DryCal-800. When the chamber is at atmospheric conditions, we tote this instrument inside the chamber, attach it to the propellant line immediate upstream of the thruster, and calibrate. In this way we can calibrate not merely the losses in the mass flow controllers, but for losses over the entire propellant delivery system! In the exact same manner as before, we can obtain a calibration curve that provides us with the conditioned commanded mass flowrate that corresponds to a desired flowrate at the thruster, this time, despite any losses throughout the whole system.

It was this new method of calibration that became my baby. I designed the system, sourced the hardware, and wrote the software. At the time of this writing, the DryCal system has been thoroughly tested and is ready, wanting, and waiting to be used.

Please excuse any typos in the above.

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