Liquid Nitrogen Propulsion System

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Abstract

This system generates thrust by expanding liquid nitrogen (LN2) into a gaseous phase and expelling it at high speeds. As the propellant is expanded, its specific volume increases, and to maintain the principle of continuity the speed of the flow must also proportionally increase. Using this technique, we measured varying thrusts of up to 22.633 N. The system utilizes a LabView driven control system to set and monitor mass flow rate. The generated thrust and the temperature of the exit fluid are measured to determine the thermodynamic state of the propellant at the exit. By comparing the thermodynamic states of the propellant in the reservoir and at the exit, we can determine the heat transfer rate to the fluid. As expected, a positive relationship between heat transfer rate and thrust was observed over eight trials.

System Discussion

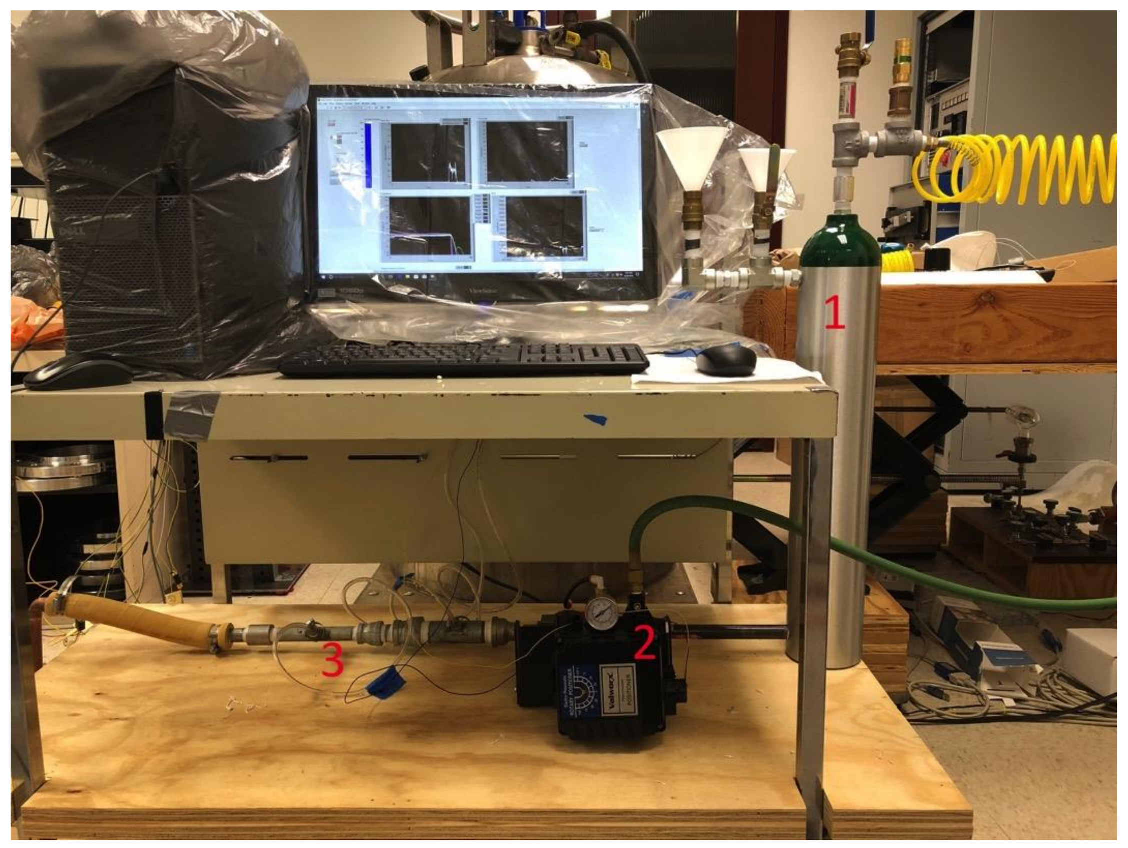

Figure 1. Propellant management system.

Propellant Management (Fig. 1)

Pushes LN2 from reservoir using compressed argon

Storage Cylinder (1):

- Liquid nitrogen is filled through the side port manifold of the cylinder
- Manifold on top of the cylinder includes a brass ball valve for boil off, a relief valve, and a pressure inlet
- Cylinder is pressurized by compressed argon gas

Actuated Cryogenic Ball Valve (2):

- Attached to a pneumatic actuator, which is then attached to an electric positioner
- Pneumatic actuator utilizes pressurized air (nitrogen gas) to open, and a spring to close
- Positioner accepts 4 – 20 mA current

Flow Meter (3):

- Utilizes a pressure transducer to convert a differential pressure to a voltage

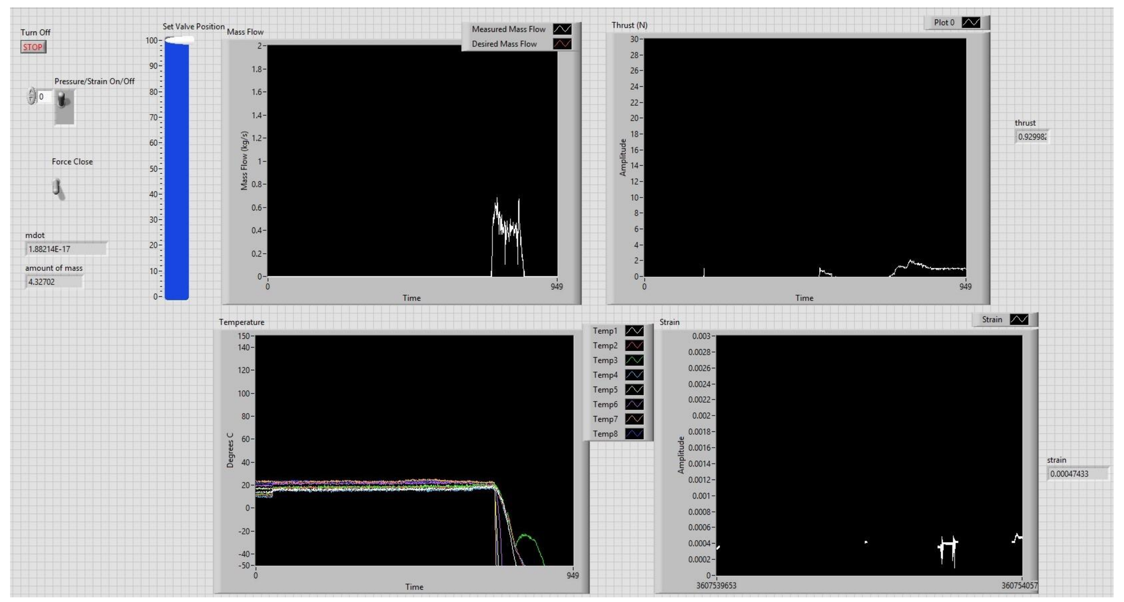

Figure 2. LabView virtual instrument control panel.

LabView Control (Fig. 2)

- Control system for mass flow rate and collects and stores data for tests from thermocouples, and transducers.
- Ability to turn on/off feedback devices, manually change the cryogenic valve position, and force close cryogenic ball valve for emergencies
- Waterproofed for performing preliminary tests with water

Theory

The thermodynamic state of a fluid describes all of its thermodynamic state variables: pressure, temperature, enthalpy, internal energy, specific volume, entropy, and quality. Within a thermodynamic state, only two state variables can be set, and the rest are then determined or locked-in by the two known state variables. A thermodynamic state also drives what phase a fluid is in and its saturation information. With this understood, by locking one state variable and adjusting another, it is possible to enact a phase change to a fluid as long as the new thermodynamic state demands the fluid be in a different phase. In this system, we set the pressure of liquid nitrogen and add heat energy to it by exposing it to hot pipe surfaces. The addition of this heat energy changes the enthalpy of the fluid, forcing changes to its thermodynamic state. When we store liquid nitrogen in a reservoir, it is a compressed liquid. As heat is added, the fluid becomes saturated, and small percentages of the fluid boil off into gas, reducing the overall density of the fluid, or increasing its specific volume. Thrust is created by expelling mass at high speeds. The more mass that is expelled, and the faster it is moving, the more thrust that will be generated. So as the specific volume of the liquid increases, to maintain continuity of the mass flow rate, the velocity of the flow must also increase. By facilitating this increase in the speed of the flow, the system generates comparatively more thrust than it would if it expelled nitrogen in just its liquid phase. Liquid nitrogen is a cryogenic fluid, meaning it has a very low boiling temperature when compared to other liquids like water. As a result, it has a more natural affinity to rapidly boil off when exposed to high temperatures than most liquids, making it a perfect candidate for an expansion-based propulsion system.

Figure 3. (Right) Expansion system enacting a phase change on the liquid nitrogen during a test.

Figure 4. Thrust measurement setup using a simply supported beam.

Expansion (Fig. 3)

- Four ½ inch vertical copper tubes that are sweated together
- Vertical orientation helps facilitate boiling and phase separation within pipes
- Pipes are heated with blow torch before testing to transfer heat to working fluid
- Thermocouples a the base of each pipe to measure pipe temperature (heated to roughly 360 Kelvin before testing, melting point of solder is 420 K)
- Thermocouples mounted at exits to monitor temperature of exit flow

Thrust Measurement (Fig. 4)

- Copper tubes mounted on simply supported beam with a full bridge force transducer
- Copper tubes connected to upstream system with flexible hose, so as thrust is produced, the copper tubes can translate freely up and down apply a bending moment to the beam
- Strain measurements are converted in LabView into force given the geometric knowledge of the strain gauge and loading locations
- Mounted with a stepped wooden jig to keep copper tubes oriented vertically
- Copper tubes rest on simply supported beam along a single line of contact using a small cylindrical metal rod, held on with zip ties to the small plywood piece seen in Fig. 4

Results

Eight trials of data were collected over three testing sessions. Both heated and unheated tests were performed. The mass flow rate, thrust, temperature of the copper pipes, and the temperature of the exit fluid were recorded by the LabView interface for each trial. The table below summarizes notable values from testing.

Table 1. Summary of testing.

Quantity	Value	Position of Trial in Session	Trial Description
Greatest Measured Thrust	22.633 N	1st	Unheated
Greatest Measured Flow Rate	1.85 kg/s	1st	Unheated
Greatest Calculated Heat Transfer Rate	13.26 kW	1st	Unheated
Greatest Calculated Exit Quality	0.08429	1st	Heated
Longest Trial	12.1 s	2nd	Heated
Average Trial Length	7.1 s	N/A	N/A
Average Measured Exit Temp	-172.26 C	N/A	N/A
Coldest Measured Pipe Temp	-92.6563 C	4th	Unheated

For each test, sporadic periods of near steady state behavior were observed. A data point within these periods of steady state was taken from each trial, and the thrust and mass flow rate values were used to derive the thermodynamic state of the fluid at the exit and the heat transfer rate to the fluid at that moment in time. In no trial did we observe a complete phase change to the gaseous state. The greatest calculated quality of the exit flow was 0.08429. During the longer trials, we observed liquid nitrogen droplets actually raining down onto the lab floor, indicating the exit quality was very low. Fig. 5 below gives the empirical relationship we determined between heat transfer rate and thrust.

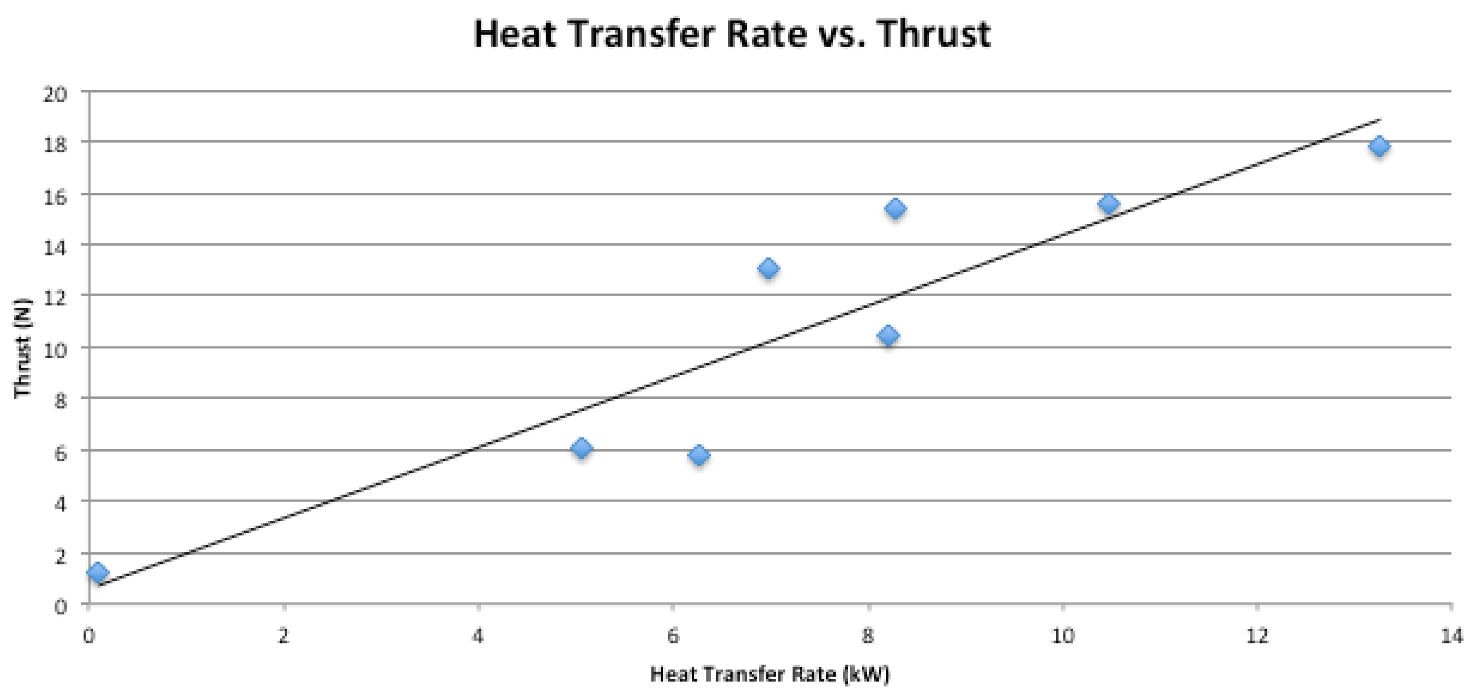

Figure 5. Empirical relationship between heat transfer rate and measured thrust.

Conclusions

- We successfully created a system to produce thrust via the expansion of liquid nitrogen
- More quantities need to be measured to more effectively determine heat transfer rate and thermodynamic state, like flow exit speed and reservoir pressure and temperature
- To achieve steady state conditions for longer periods of time, a more effective heat addition technique is required
- To achieve consistent thrust measurements, we need to minimize unintended heat transfer from system components. In the early trials of a testing session, we observed error in mass flow measurements and comparatively large thrust measurements. The system needs to be cooled with LN2 for one or two trials before data becomes valid.

Acknowledgments

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References

Borgnakke, Claus, and Richard E. Sonntag. Fundamentals of Thermodynamics. 8th ed., Wiley Global Education, 2012.

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