Automation of CO_2 Distillation for Telescope Mirror Cleaning

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1 Abstract

High-pressure liquid carbon dioxide has been used as a way to clean sensitive surfaces such as mirror optics for some time. The cleaning process is based on the rapid expansion of liquid carbon dioxide through an orifice or nozzle. Micron- and submicron-sized particles are dislodged from the mirror surface by frozen carbon dioxide snow particles and then swept away in a cloud of carbon dioxide vapor. The Hobby-Eberly Telescope (HET) is part of McDonald Observatory located outside Ft. Davis, Texas. The HET employs a liquid carbon dioxide cleaning system to remove unwanted particles from its primary reflector. In addition, the HET maintains, but is not currently using, a manual method of distilling high-purity carbon dioxide from a source of lower-purity carbon dioxide. This report will describe the work performed during the summer of 2009 to automate the distillation process and as a result allow the HET to switch from delivery of high-purity carbon dioxide to delivery of low-purity carbon dioxide, saving the HET approximately $13,000 annually.

2 Background Information

There have been several articles published on the methodology and effectiveness of cleaning with high-pressure liquid carbon dioxide.[1] Several variables have been identified as having a large impact on the effectiveness of this cleaning process. Among them are nozzle shape, pressure, and the purity of the carbon dioxide used. It has been demonstrated that cleaning with high-purity carbon dioxide results in a cleaner surface. For organizations wanting to implement this type of cleaning strategy, a problem exists. How can high-purity carbon dioxide be obtained and stored in a relatively inexpensive way?

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[1] E. Hill, Carbon Dioxide Snow Examination and Experimentation, Precision Cleaning, Feb. 1994

Typically there are two choices. High-purity carbon dioxide, also referred to as food-grade carbon dioxide, can be delivered by tanker truck to a cleaning site and stored in some type of bulk tank. The delivery of this grade of carbon dioxide can be quite expensive when compared with the other, lower-cost alternative of welding-grade carbon dioxide. If welding-grade carbon dioxide is used, then an additional on-site distillation process must be employed so that the cleaning surface is not contaminated in the process of cleaning. The rough cost difference between the two grades is around 15 cents per pound. Depending on the volume used in the cleaning operation, the savings can be significant. In this case, for example, the HET uses approximately 10,000 pounds of liquid carbon dioxide every six weeks to clean the primary mirror. By switching to lower-grade carbon dioxide, the annual savings to HET is approximately $13,000.

Obtaining high-purity carbon dioxide from a lower-purity carbon dioxide is not that different from a standard distillation sequence. Inside a bulk storage tank, there is a combination of liquid and vapor carbon dioxide. The contaminants are found mostly in the liquid and not in the vapor. Because of this, the pure vapor can be collected from the bulk storage tank and converted into high-purity liquid carbon dioxide by increasing its pressure and reducing the temperature. Once this high-purity liquid carbon dioxide has been distilled, it can be stored in a separate vessel that can be used during a cleaning operation. The HET process differs from other industrial cleaning operations in that they use an on-demand system, and typically have a much smaller surface area to clean. A typical on-demand system can only produce a small amount of liquid carbon dioxide without being prohibitively expensive. The HET primary mirror is part of the largest reflecting telescope in the world with an aperture of 9.2m. Given this large size, the HET carbon dioxide distillation system was designed to produce and store large quantities of high-purity carbon dioxide to be available for cleaning operations.

The HET system consists of five components to perform this distillation process. A bulk storage tank is used to hold the raw carbon dioxide. A pressure booster pump is used to pull and compress vapor from the bulk tank. The high pressure carbon dioxide vapor then passes through a heat exchanger where it condenses back into a liquid. The high-pressure liquid is stored temporarily in ten, high-pressure cylinders. The last component of the distillation system is another storage tank used exclusively for high-purity carbon dioxide. Transferring liquid carbon dioxide from the cylinders into the tank is accomplished through a cryogenic valve. This valve isolates the high-pressure output of the booster and high-pressure cylinders from the low-pressure high-purity storage tank.

Due to the design of the distillation system, manual operation involves setting the system up to run and monitoring it every 30-45 minutes. Monitoring the system is required for two reasons. First, once the system has distilled enough liquid carbon dioxide to fill the high-purity storage tank, the system does not need to run any longer and must be shut down. Second, as the pressure in the high-pressure storage cylinders increases, the booster will shut down due to an output pressure limit. To address these two issues, manual intervention involves transfering liquid carbon dioxide every 30-45 minutes to reduce the pressure in the high-pressure storage cylinders and to monitor the liquid level in the high-purity storage tank. This transfer is accomplished through a cryogenic valve located between the high-purity storage tank and the high-pressure cylinders.

The goal in automating the distillation process is to have the high-purity tank filled automatically so that when cleaning is required, an adequate amount of liquid carbon dioxide is available. The system should detect a low liquid level in the high-purity tank, initiate the distillation process, perform transfers from the high-pressure cylinders to the high-purity storage tank, and shut down when the tank is full.

3 Implementation

The basic idea in automating the distillation process is to install a programmable logic controller (PLC) and connect it to a series of electronically-actuated solenoid valves and sensors in the distillation system. In this way, the PLC can monitor the pressures and temperatures present and open or close the appropriate valves to handle the situation.

The first step in implementation was to study the manual operation of the system. By doing this, a better understanding of how the system works and a rough estimate of the rate of production was obtained. Another advantage to operating the system manually is that it becomes easier to understand what types of conditions can exist and how the automated system might handle them. This phase of the project lasted for approximately six weeks. During those six weeks, preliminary programming for the PLC was written and tested using a simple test-bench setup that modeled the actual system. Potentiometers were used to model sensors and LEDs were used to indicate contact-closure of output switches representing solenoid valves. In addition to preliminary testing, extensive documentation was developed for the new automated system. Besides the obvious usefulness of operational documentation, employees of the HET desired a document that would help them expand the system in the future.

Several issues were addressed during these first six weeks. In order for the automated system to be aware of the liquid level in the high-purity carbon dioxide tank, and thus know when to shut down, the existing liquid level gauge needed to be fixed. This amounted to replacement of a pressure transducer. Second, in order to effectively transfer high-purity liquid carbon dioxide between the high-pressure cylinders and the high-purity storage tank, the cryogenic valve between the two needed repair. Initial diagnosis pointed towards a leaking gasket, but upon further investigation it was discovered that the bolts securing the valve assembly simply needed to be tightened. The last major issue was with the booster pump component. The booster pump is used to pull carbon dioxide vapor from the bulk storage tank and increase its pressure. During manual operation of the system, several leaks in the booster were discovered and fixed using a rebuild kit from the manufacturer.

Subsequent installation of the automated system consisted of placing sensors and solenoid valves in the distillation system. Following that, cable and conduit were prepared to connect the pressure sensors and solenoid valves to a junction box located conveniently on the side of the bulk tank. Cable and conduit were also used to connect the junction box to a Hoffman box that holds the PLC and the associated circuitry. Once the hardware was installed, the final step in implementation was running and debugging the PLC code. This consisted of checking to make sure that each sensor could be read and that each solenoid could be actuated. In addition to this basic functionality, logic and sequencing of the PLC programming code was validated. Once the distillation system was running, the remaining work consisted of adjusting pressures and levels in the system to optimize the distillation process. During the final week of the project, electrical schematics, wiring diagrams, parts lists, and flow charts were finalized as part of the documentation package delivered to the HET staff. Components in the actual system were labeled to match this documentation to facilitate future development of the system.

4 Safety Considerations

When dealing with a system that uses cryogenic fluids, safety considerations must be taken into account. These considerations are mostly related to the danger of trapping a cryogenic fluid in a section of pipe or other closed container. If the trapped fluid is allowed to absorb heat, it begins to evaporate and pressure builds. If not given the appropriate relief, this pressure can cause an explosion. To mitigate these concerns, the design of the system makes use of two types of safety precautions.

The first type of precaution involves the addition of hardware in the system to handle excessive pressures. Relief valves are located in places where cryogenic fluid may be present in a closed space. A relief valve is rated at a specific pressure and will open if that pressure is exceeded. Rupture discs provide another venting strategy. These are typically rated at higher pressures and serve as a secondary method of venting pressure.

The second type of precaution is related to the configuration of how the PLC handles the solenoid valves in the system. Each solenoid valve can be configured as normally closed or normally open. For example, a normally closed valve will be closed in the de-energized state and will require power in order to open. Due to the design of the system, the fail-safe condition for all valves is normally closed. By using this strategy, if there is a power failure or other unanticipated event, power is removed from all solenoids and the system shuts down. Each section of the system is designed to handle the pressures that would normally be present when all valves are closed.

As an additional safety consideration, the remote location of McDonald Observatory and the occasional power interruption must be taken into account. As previously mentioned, a power outage will result in all valves closing leaving the system in a stable state. When power is restored, the PLC is automatically reset and begins a check of pressures in the system to determine whether it is safe to begin running. In other words, a power interruption is equivalent to the normal power-on cycle for the PLC.

5 Immediate Benefits

The most obvious benefit is that the system can now fill the high-purity storage tank automatically and be ready for the next cleaning operation. This can now happen with minimal operator intervention. Complementing this improvement, the HET can now switch to purchasing low-grade carbon dioxide on a regular basis and enjoy the $13,000 annual savings that come from this switch. With these savings, the cost of the distillation equipment is recovered in about one year.

Secondary to those two major benefits, there are several other benefits to the HET that are less obvious but nevertheless important to mention. By automating the distillation process, the throughput of the system can be studied and better understood. For example, the PLC will keep track of the time required to fill the high-purity storage tank. This information can be used to better predict how often carbon dioxide needs to be delivered, as well as any number of optimization scenarios related to the cleaning process. The PLC can also keep track of how long each component in the system has been operating. The booster pump is probably the most obvious component needing monitoring, since it contains parts that have a manufacturer-documented lifetime and need to be replaced at regular intervals.

6 Opportunity for Future Work

Automating the distillation process is only the first step in a much larger plan to fully automate the cleaning process of the primary mirror for the HET. By utilizing the same basic approach, the next step is to automate the liquid carbon dioxide pump that delivers cleaning liquid to the point of delivery at the mirror. To accomplish this, a few additional solenoid valves must be installed to replace existing manual ball valves. In addition, the pump's control unit must be connected to the PLC so that the pump's rate can be adjusted as needed. Moving further downstream in the system, the next opportunity for automation is the delivery of liquid carbon dioxide to the mirror itself. Currently, a wand operator standing on a lift manually sprays the mirror in a somewhat methodical fashion. Ideally, the process of spraying down the mirror should not involve any kind of human intervention.

By creating a mechanism for spraying the mirror automatically, the cleaning process can be much more reliable and robust across multiple cleanings.

7 Conclusion and Reflection

This summer project was particularly enjoyable for me, as it allowed me to use my software development skills coupled nicely with experience working with a pressurized gas and liquid system. Over the ten weeks I spent working on this project, I was also able to study some of the engineering and maintenance tasks required to deliver a functioning instrument that scientists could use to complete their research.

Although I did not have much opportunity to advance my knowledge in the field of astronomy, I did get to meet and talk with several visiting astronomers about their research and about their life. I find it fascinating to discuss what it means to be passionate about the work you do with individuals who clearly have a passion for their field of study.

Last, I would like to mention several opportunities I had over the summer to do work that I had never done before. I was able to use a milling machine to produce a mounting bracket. I gained a lot of experience in learning how to appropriately size, punch, and tap screw holes in metal. I learned how to mount anchors in an existing concrete pier. I gained experience with how to map out, purchase, and assemble complex tubing and valve structures. And I also gained experience in designing practical circuits for solenoid valves and sensors.

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