Fermilab

Particle Physics Division
Mechanical Department Engineering Note

Number: MD-ENG-225 Date: 22 February 2009

Project Internal Reference: None

Project: MicroBooNE

Title: Cooldown Report

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Key Words: Cooldown, MicroBooNE, Pressure drop, Plate-fin heat exchanger, TPC, TPC wires

Applicable Codes: ASME Section VIII (Heat exchanger), ASME B31.3 (Piping)

Introduction / Abstract

The process of cooling down the cryostat without breaking any components such as the TPC, time projection chamber, is a critical element to the MicroBooNE project. An Excel spreadsheet was created to calculate the length of time needed to bring the cryostat down to a temperature so that liquid argon can be used without thermally shocking the TPC's wires.

A system comprised of a compressor, piping, molecular sieve, and heat exchanger was sized according to the values calculated from the workbook called "Cooldown Calculator". It consists of worksheets such as Cooldown, Convection, Pressure Drop, Inlet and Outlet Sparger, Temperature Data, Runge Kutta, and Heat Exchanger. Cooldown time was estimated from the energy balance differential equation and subsequently solved using the Runge-Kutta numerical method.

Description

Given the TPC's wire importance to the experiment, its stress drives the cooldown time. 304V stainless steel, fortunately, has a very high yield and ultimate strength compared to the standard 304 stainless steel. Its ultimate strength is roughly 3 times stronger than SS304 which is required due to the stresses associated with its pre-tension of 1 kgf. According to the spreadsheet, only 54 MPa is available for thermal stress whereas the amount in pre-tension is 555 MPa because the wire diameter is only 150 microns. This results in a temperature difference (ΔT_f) between the frame the wires are mounted on and the wires themselves of only 16.7 K to be within 1/3rd of the ultimate strength which leads to the assumption of a long cooldown period.

Due to the complexity of the model, certain simplifications were made so that hand calculations were feasible. Effects of a large gradient in the fluid were ignored and instead the system was treated as a lumped capacitance model which is valid for small Biot numbers (< 0.1). Another assumption was that the wires are nearly the same temperature as the gas as a result of their small mass. With these simplifications, an energy balance equation, Eq. (1), was developed to find the temperature of the system as a function of time:

$$(m_a c_{p,a} + m_s c_{p,s})\frac{\partial T}{\partial t} = \frac{q_{@90K}}{300K - 90K}(T_o - T) - \dot{m} c_{p,a} \Delta T_f - h_r\left(T^4 - \left(T - \frac{\Delta T_f}{2}\right)^4\right) \qquad (1)$$

Where:

m_a	mass of argon
m_s	mass of 304 SS
$c_{p,a}$	specific heat of argon
$c_{p,s}$	specific heat of 304 SS
$q_{@90K}$	heat flow rate when T = 90K
T_o	outside air temperature
ΔT_f	fluid temperature gradient
h_r	radiation coefficient
$\dot{m}$	mass flow rate of argon

Because this equation is an atypical, nonlinear ODE, an analytical equation was not easily obtainable. Therefore a numerical approach was used called the Runge-Kutta method. This essentially considers it linear over small intervals so caution must be made to ensure the time interval is small enough, thus a default value of one hour was used. This equation gives a good approximation of how each parameter affects the cooldown time so if a faster cooldown time is recommended, then it could be adjusted accordingly by increasing the argon gas flow rate or reducing the mass of steel. However, it must be

noted, that this requires many iterations for the fact it has to iterate for a month's worth of data so Excel must do iterative calculations until it all converges.

Since $\dot{m}$ was derived from 4 volume changes per hour, a calculation was performed to see if this flow rate gave a reasonable time to reduce the temperature down to the specified cooldown temperature. With the level of complexity of the model, a CFD analysis is also being performed to see how well it matches up to the estimates given by the workbook. It will provide supplemental information that can be used to give a more detailed assessment. Because bowing of the TPC frame is a large concern, the temperature of the fluid needs to be determined along each point of the frame. Its long length along the cryostat of nearly 33 ft can easily lead to high unexpected stresses if there is a significant difference in temperature between the bottom frame and the top.

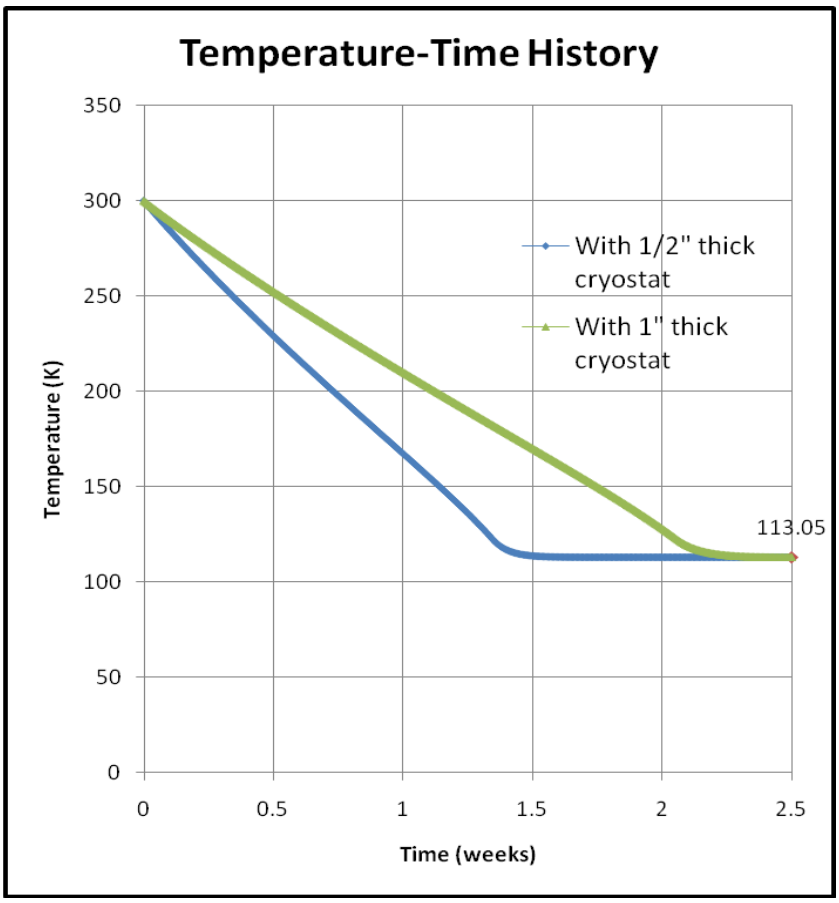

Figure 1: Screen capture of the cooldown calculator

Analysis

With a 1” thick 304 stainless steel vessel and near 5-ton TPC, it was shown that it would take a considerable time to cooldown without overstressing the wires. In order to get it down to a temperature that allows for liquid to be used, the TPC should be no more than 25 K above the liquid’s temperature at the end of the cooldown operation. As can be seen in Fig. 1, it will take over 2 weeks to reach 115 K with the current flow rate of 36.86 lb/min which is about a 0.5 K/hr cooldown rate. Thinning the cryostat wall offers a much quicker cooldown rate (less than 1.5 weeks) and over a 60% reduction in stainless steel mass. Shown in the temperature vs. time graph, the cooldown happens relatively linearly due to the thermophysical properties, such as density and specific heat, changing in a way that balances against the increase in heat load through the insulation. Since the properties change with pressure and temperature, an equation was made vs. temperature for atmospheric pressure and at 15 psig. Then a simple linear interpolation or extrapolation gives the values at the cryostat’s pressure. The system reaches a stopping point of 113 K. This is because the gas’s lowest temperature is set to 100K and is unable to outweigh the heat leak through the insulation at this point. A transition then would occur to start flowing liquid argon into the system in order to cool it down to its operating range.

In order to gain a little more understanding of what is going on inside the vessel, the Convection worksheet estimates from the values shown above what the actual temperature difference between the fluid and surface temperatures are, but caution must be made since the fluid is not a constant. It was assumed to be a flat plate with a constant fluid temperature until results from the CFD analysis give more insight into the actual gradient. In the calculation, it is shown that it is only a 1.78 K difference—well short of the allowable 16.7 K. So a possible recommendation can be made to increase the temperature difference going in and out of the cryostat to reduce the cooldown time if the CFD results show similar results.

Another sheet in the Excel workbook was made to obtain pipe sizes and pressure drops. Not only must this system cooldown the cryostat, it must initially warm it up to drive out moisture. With roughly 100’ of piping with valves, a molecular sieve, spargers, warm gas, and a heat exchanger, pressure drop becomes a large concern especially with only 15 psi allowed. With that much piping and substantial size of the cryostat, approximately 28500 scf of argon gas will need to be provided by either a tube trailer and/or large Dewar(s). Based on the fact that pressure drop is proportional to the inverse diameter of piping to the 5th power, a large diameter is needed to minimize pressure drop, 2” schedule 10 piping was calculated to be within the allowable range with a total pressure loss of 11 psi. 40% of the allowed pressure drop is due to the two passes through the heat exchanger.

Pressure drop and space are two big issues that are taken into account with the heat exchanger. A vertical orientation was chosen to minimize floor space since vertical space is not a limiting factor. Plate-fin heat exchanger was chosen from naturally having the highest surface area density. The unit will have three streams to minimize its floor footprint and piping with argon gas going through two streams in a closed loop and nitrogen through the third. Effectiveness easily surpasses 95% so that nitrogen costs are minimal. Since nitrogen is relatively inexpensive, it will be purged into the atmosphere.

Conclusion

At this point, nearly every aspect of the cooldown system is large in size. Even with a flow rate of ~37 lb/min it will take over 2 weeks to reach < 115 K with a 1” thick cryostat. 75000 lbs of steel and a low temperature difference contribute the most to the cooldown time. A ½” thick cryostat drops this time considerably with it taking just under 1.5 weeks. The amount of complexity to this system makes the validity of the calculations suspect resulting from its transient nature and composite 3D bodies. Radiation is built into the equations, but currently is omitted for conservative results. If the gradient in the fluid is minimal around the TPC itself, then it could be recommended to increase ΔT_f because the convection calculation showed less than a 3 K difference between the fluid and the TPC frame. Increasing the flow rate is not recommended because it would only increase the components’ sizes further. Until a full CFD analysis is performed, the expected cooldown time is 1.4 weeks before liquid can start being pumped into the cryostat.

The spreadsheet for the cooldown calculator will be placed in the same docdb number so that any input value can be changed as the project gets more refined. Macros should be enabled to use this spreadsheet as well as iterative calculations. It should be noted that the calculator is for estimation purposes only and its results should only supplement engineering judgment by giving a basis and insight into the behavior of the system.