Forced two-phase helium cooling scheme for the Mu2e transport solenoid

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Abstract. The Mu2e Transport Solenoid (TS) is an S-shaped magnet formed by two separate but similar magnets, TS-u and TS-d. Each magnet is quarter-toroid shaped with a centerline radius of approximately 3 m utilizing a helium cooling loop consisting of 25 to 27 horizontal-axis rings connected in series. This cooling loop configuration has been deemed adequate for cooling via forced single phase liquid helium; however it presents major challenges to forced two-phase flow such as "garden hose" pressure drop, concerns of flow separation from tube walls, difficulty of calculation, etc. Even with these disadvantages, forced two-phase flow has certain inherent advantages which make it a more attractive option than forced single phase flow. It is for this reason that the use of forced two-phase flow was studied for the TS magnets. This paper will describe the analysis using helium-specific pressure drop correlations, conservative engineering approach, helium properties calculated and updated at over fifty points, and how the results compared with those in literature. Based on the findings, the use of forced-two phase helium is determined to be feasible for steady-state cooling of the TS solenoids.

1. Introduction

Mu2e is an experiment currently under construction, located at Fermi National Accelerator Laboratory (Fermilab) which aims to detect muon to electron conversion in the field of a nucleus [1]. The experiment will utilize 3 superconducting solenoids to accomplish this task, the Production Solenoid (PS), the Transport Solenoid (TS), and the Detector Solenoid (DS). All three solenoids will be cooled to liquid helium temperatures.

The TS consists of two separate cryostats, the TS-u (Transport Solenoid, upstream) and the TS-d (Transport Solenoid, downstream). Each of the cryostats has several "coil modules" assembled together which form either the TS-u or TS-d, with 13 of the coil modules in the TS-u and 14 of the coil modules in the TS-d. These coil modules consist of the superconducting coils, an aluminum shell, helium cooling lines, and other miscellaneous hardware [2], [3].

Conceptual design of the TS cooling system utilized a liquid helium single phase cooling scheme with circulation pump. This cooling system was designed to keep fluid temperatures inside of the TS below 4.8 K at a flow rate of 50 gm/sec and a pressure of 297 kPa absolute. Although the single phase cooling scheme is a viable option for the TS, a study of a forced two-phase cooling system was conducted as forced two-phase cooling offers certain inherent advantages with respect to a single phase system. These advantages include thermal protection from extraneous heat loads (provided the flow is

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two-phase, heat will be absorbed latently), lower mass flow rates, removal of a circulation pump (which is required in the single phase scheme), and the ability to provide nearly isothermal cooling.

2. Mu2e cryogenic distribution layout

The Mu2e cryogenic refrigeration facility employs two Tevatron-style satellite refrigerators which provide liquid helium to the experiment. Approximately 500 feet of outdoor transfer line separate the refrigeration facility from the Mu2e experimental hall. Upon entry into the Mu2e building, helium is routed through a large valve box known as the "distribution box" and into a helium storage dewar. After leaving the dewar, helium flow re-enters the distribution box, is split, and is routed to four separate valve boxes called "feedboxes" in four shorter and separate transfer lines. These feedboxes distribute helium to each of the four Mu2e cryostats independently. As mentioned previously, the TS magnet consists of both the TS-u and the TS-d, thus two separate feedboxes are used for the TS as a whole. Upon leaving the feedboxes, helium flows through another set of independent transfer lines down into the experimental pit where it can be delivered to each of the cryostats. After cooling each solenoid, helium is returned to the respective feedbox, back to the distribution box, and then finally to the cryogenic refrigeration facility. A generalized schematic of the helium distribution system can be seen in Figure **1**.

As seen in Figure 2 both the TS-u and TS-d are quarter-toroid shaped and have centerline radii of approximately 3 m. Helium tubing is arranged in a helical configuration inside of each of the TS cryostats to consist of 25 horizontal-axis rings connected in series via crossover tubing; with 18 of the 24 rings having a 1 m diameter and 7 rings having a 1.25 m diameter (see Figure 3 for reference).
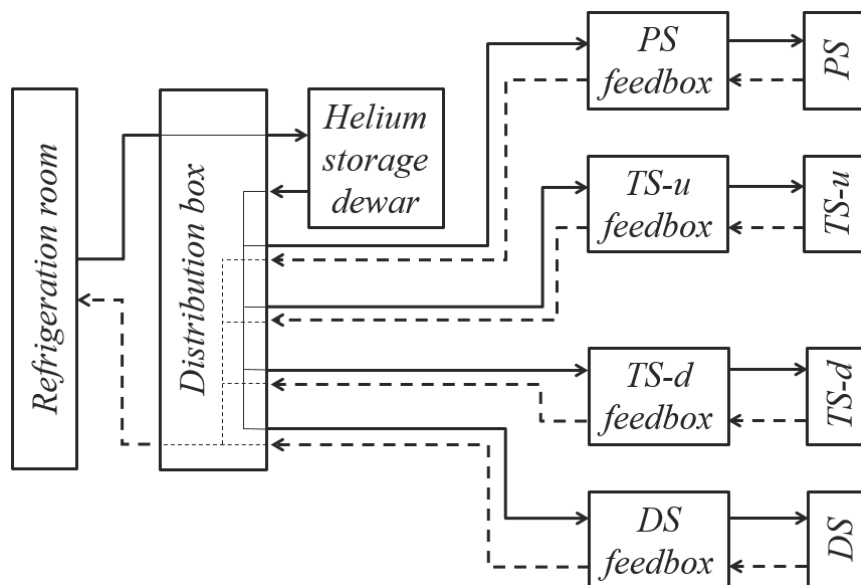

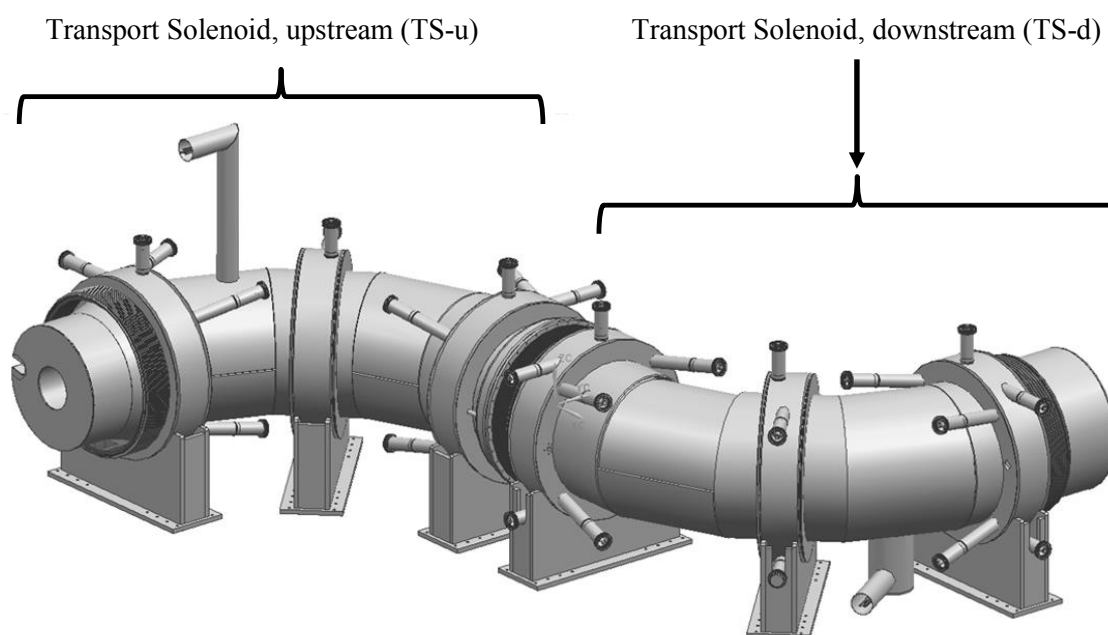**Figure 1.** Generalized helium flow schematic for the Mu2e experiment.

Transport Solenoid, upstream (TS-u)   Transport Solenoid, downstream (TS-d)

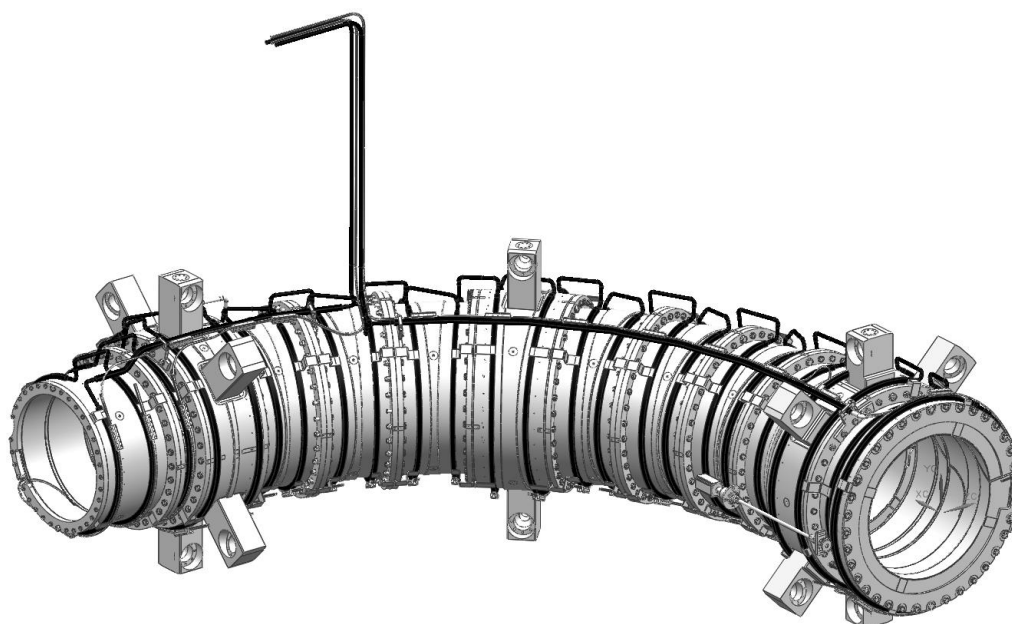**Figure 2.** Three-dimensional model of the Mu2e Transport Solenoid (TS).

Figure 3. TS-u with cryostat and shielding removed; He cooling tubes shown in black.

3. Calculation methodology

The forced two-phase helium cooling analysis begins at the exits of the TS-u and TS-d feedboxes, where the conditions presented in Table 1 are assumed. Applicable fluid properties are calculated using REFPROP software version 9.1 [4].

Table 1. Summary of calculation inputs.

	Feedbox exit
Helium flow rate, gm sec^{-1}	9
Helium vapor quality	0.00
Helium temperature, K	4.77

Table 2. Feedbox to magnet transfer line layout and dimensions.

	TS-u	TS-d
Transfer line length, m	25.4	20.0
Transfer line 90° bends	7	5
Transfer line elevation change, m	5	7
Transfer line pipe diameter, mm	13	13
Transfer line heat load, W	14	14
Solenoid piping length, m	105	105
Solenoid 90° bends	103	103
Solenoid pipe diameter, mm	22	22
Solenoid total heat load, W	43	43

After leaving the feedboxes, helium travels through individual transfer lines and arrives at the respective cryostat inlets. The helium state at the TS-u and TS-d inlets is determined by use of a two-phase helium pressure drop correlation developed by Rane et al., [5], and with data provided in Table 2. For horizontal flow in liquid helium transfer lines at pressures ranging from 1.1 to 1.4 bar, the correlation of Rane [5] has an accuracy within 5% of pressure drop seen during testing.

Next, helium flow enters the respective TS-u and TS-d piping helix. When entering the TS helixes, helium arrives at the top of the first coil and makes its way through the coils, eventually terminating at the top of the 25th and final coil. Helium conditions are re-calculated 50 times in the helix, once at the highest point in each coil and once at the lowest point in each coil. Pressure drop between the high and low points is calculated using the Rane correlation, [5], for vertical downwards flow and the Friedel correlation [8] for vertical upwards flow. The Friedel correlation proved to yield more conservative pressure drop estimates as compared to correlations for two-phase helium flow in vertical tubes developed by Khalil [9]. Further contingency is added to the calculation by assuming that the static head which was gained in the downwards flow segments is not recovered in the upwards flow segments.

Lastly, the Rane correlation, [5], was re-used to calculate the helium conditions upon returning to the feedboxes. Results of this calculation are presented in Table 3 and Figure 4.

Table 3. Helium temperature distribution along the length of the TS-u magnet.

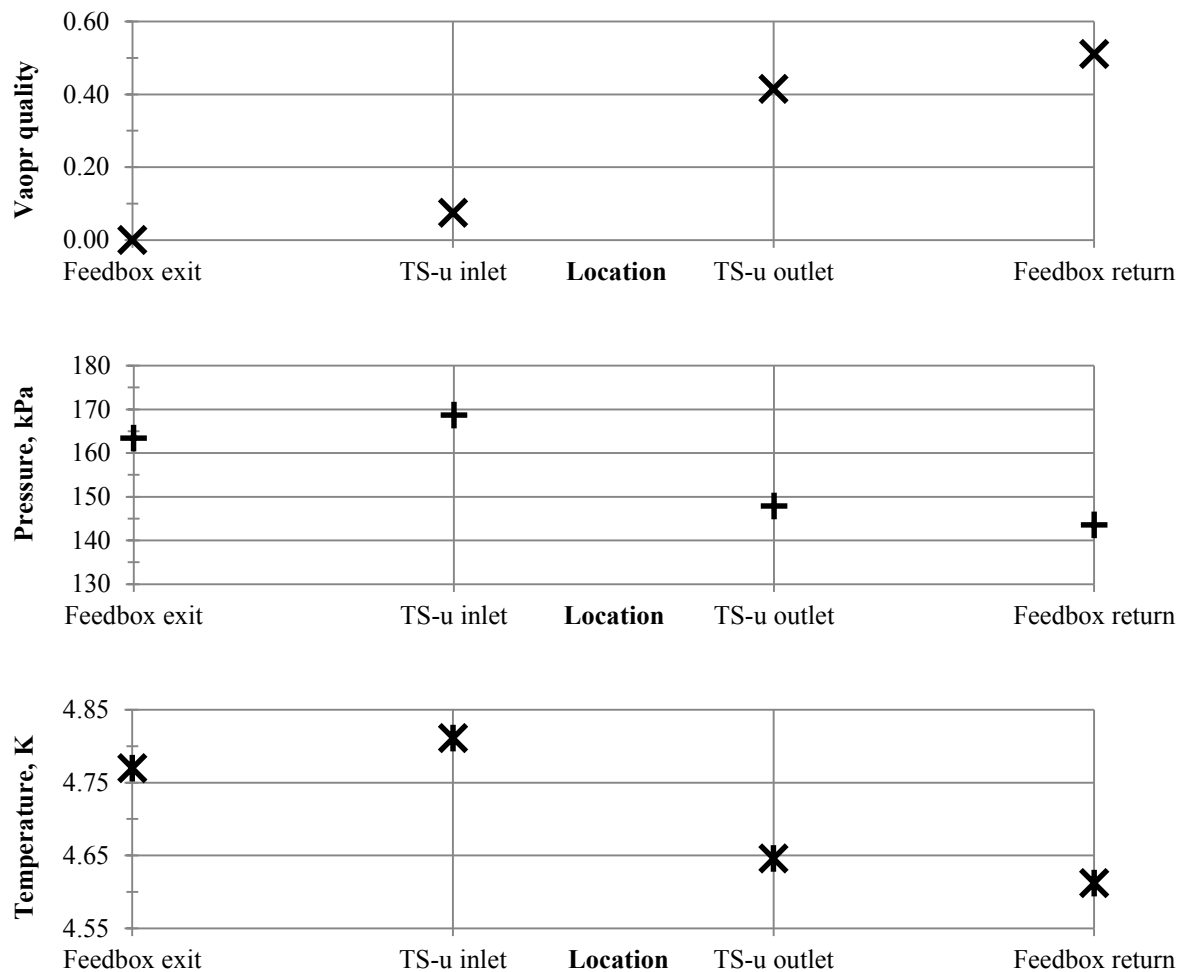| TS-u coil	Two-phase helium temperature, K
1	4.82
5	4.79
10	4.76
15	4.73
20	4.69
25	4.67

Figure 4. Helium property variation along the piping route considered in this calculation. An increase in fluid pressure occurs between the exit of the feedboxes and the TS inlets due to an elevation change (presented in Table 2).

4. Garden hose pressure drop

Possibly the largest uncertainty encountered when designing a forced two-phase helium cooling system comes in trying to predict two-phase pressure oscillations. This is especially true when tubing is arranged in a helical configuration such as in the TS.

The cause of these oscillations can be well visualized by imagining a coiled garden hose half full of water hanging from a horizontal peg. If it is desired to rid the hose of water, additional pressure is required to force the water out of the hose due to the various heads of water in each of the coils. Furthermore, the pressure required to "push" the water out of the hose will oscillate as slugs of liquid exit the hose. This additional pressure drop and oscillation is directly related to the two-phase temperature; therefore to achieve true steady-state operation, sound engineering design is needed such that these garden hose effects are minimized.

While forced two-phase helium cooling schemes with similar tubing arrangements to the TS have been used successfully in the past, available literature pertaining to oscillatory garden hose behavior is scarce. Most of the studies concerning the garden hose effect have been authored by M Green et. Al

and T Haruyama et al. [6], [7]. As observed by Green [6], a rough approximation of garden hose pressure drop can be obtained by use of Equation (1),

$$\Delta p_{GH} = \frac{0.8x_{exit}}{2}\left[\left(\rho_l - \rho_g\right)\big|_{inlet} + \left(\rho_l - \rho_g\right)\big|_{outlet}\right]dNg\cos\theta \qquad (1)$$

where x_{exit} is the vapor quality at the exit of the coil path, $\rho_l - \rho_g$ is the density difference between the liquid and gas phases (evaluated once at the inlet and once at the outlet of the tubing path), d is the coil diameter, N is the number of coils, g is the acceleration due to gravity, and $\cos\theta$ equal to 1 for vertical flow.

When the calculated TS steady state two-phase conditions are applied to Equation (1), approximately 7 kPa of pressure drop related to the garden hose effect is predicted, which is much less than the calculated pressure drop seen in Figure 4 that did not include static head recovery. As verification, conditions from Green et al. [11], were used in the TS two-phase cooling calculations, resulting in approximately 4 times the pressure drop observed by Green [11]. Note that a pressure drop estimate calculated using equation (1) was given in Green [11]. This estimated pressure drop was 24 kPa (not including any oscillatory garden hose effects), which is comparable to the 20 kPa pressure drop observed by Green [11] during testing.

5. Impact analysis of garden hose pressure drop

To better understand the implications of any garden hose pressure oscillations, a thermal study was performed using ANSYS software to detect maximum superconductor temperatures inside of the TS. TS-u coil module 3, consisting of helium cooling coils 4 and 5 was used for the study, as its 9.7 W heat load is highest amongst the TS-u coil modules (for contingency, the heat load is multiplied by a 1.5 safety factor in Table 4). For reference, superconducting cables used in the TS reach critical temperature at 6.7 K.

To develop a baseline, a simulation was performed with predicted two-phase steady-state helium conditions calculated earlier in this paper. The convection coefficient was estimated using [10]. Next, worst-case scenario oscillation data obtained from running two-phase systems was applied to the steady-state simulation. These conditions included a fluid temperature oscillation period of 30 sec (see Reference [11]) where helium temperature varied from 4.809 K +0.200 K and -0.100 K (see Reference [12]). The results of the thermal study are presented in Figure 5. As seen in Figure 5, coil temperature oscillation is approximately 30% of the fluid temperature oscillation. This relationship between coil temperature oscillation and fluid temperature oscillation will change with fluid oscillation period. As the 30 sec oscillation period used for the transient analysis was obtained from worst-case scenario data, a strong likelihood exists that TS oscillation periods and therefore coil temperature excursions will be smaller than calculated.

Table 4. Piping layout and dimensions.

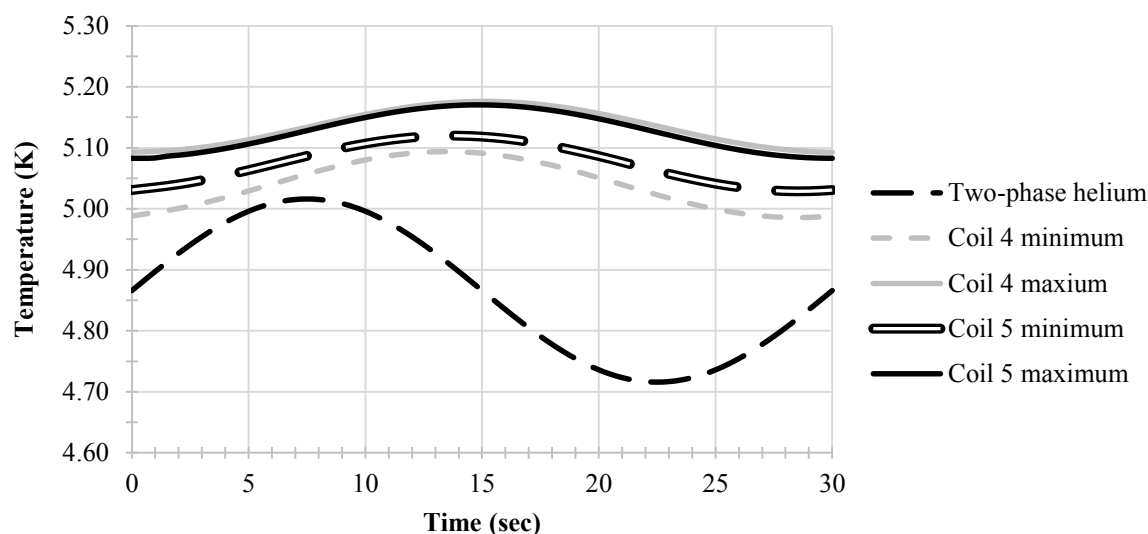|	Steady-state simulation	Garden hose oscillation simulation
Helium temperature, K	4.81	5.01 to 4.71
Heat load, W	14.58	14.58
Convection coefficient, W m^{-2} K^{-1}	1264	1264
Maximum coil temperature, K	5.10	5.18

Figure 5. Coil maximum and minimum temperatures with respect to a fluid temperature oscillation.

6. Discussion and conclusions

As seen throughout this paper, design of a forced two-phase helium cooling scheme presents many engineering challenges. These challenges are especially amplified when the piping arrangement is helical, as is the case with the TS. Therefore, conservative engineering judgment was used when analyzing the feasibility of the forced two-phase helium cooling scheme. For example, static head recovery was not taken into account in the TS piping helix, and worst-case scenario observed garden hose oscillations were assumed in the transient thermal analysis (even though the piping arrangement in [11] featured more than 6 times as many turns when compared to the TS magnets). With this conservative engineering approach, TS coil temperatures are still expected to be more than 1.5 K lower than the 6.7 K critical coil temperature.

It should be mentioned that helium is expected to transition from plug to wavy/stratified flow inside of each TS magnet. This was deduced from a modified Baker diagram for horizontal two-phase helium flow by Theilacker et al. [13]. As the flow inside of the TS magnets passes through 25 coils and 103 90° bends in crossover pipes, pipe walls are expected to be wetted throughout the length of each TS.

Ultimately, testing would provide the best simulation of TS thermal performance. At the time of this writing, a testing plan is being evaluated which could confirm the anticipations of this forced two-phase cooling scheme design.

7. Acknowledgements

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