Modeling Heat Losses in PIP-II Gallery Building Distribution Lines

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Abstract

In support of PIP-II development, thermal losses throughout radio signal and cooling water distribution networks were modeled and analyzed in worst-case and worse-than-worst-case scenarios. It was found that conduit surfaces may reach mildly dangerous temperatures up to 125°F, therefore some safety barrier is recommended. These temperatures are not, however, particularly dangerous to the conduit itself, meaning that system can operate long-term without excessive wear. Other findings indicate that the current air conditioning system can accommodate all thermal losses while maintaining a 25°C ambient temperature for human operators.

Introduction

To advance the science of particle physics, FermiLab intends to construct a new proton accelerator, the Proton Improvement Plan – II (PIP-II), which will augment the capabilities of its accelerator complex. This linear accelerator, or linac, will utilize numerous super cooled cavities (grouped into cryomodules), each tuned to a specific electromagnetic resonance. This resonance will be powered and controlled via continuous radio signals. To safely and efficiently transmit these signals from generator to cavity, many hundred feet of conduit will be implemented. While safer much more effective than open-air transmission, conduits provide their own challenges. These transmission lines will attenuate signals, or dissipate some of the input power into random particle oscillations, i.e. thermal energy. Similarly, individual power amplifiers and other devices will be partially cooled by water, but this water travels through un-insulated pipes, also dissipating thermal energy into the surrounding environment. Both of these distribution networks will be largely housed in a gallery building, in which human operators must be able to work. Before proceeding with further design and construction, it is pertinent to analyze the generation and movement of this thermal energy. Namely, this work aims to determine the maximum surface temperatures of conduit lines for human safety and part functionality, as well as determine the maximum power dissipated by both distribution systems to the gallery air as heat, which will be used as a benchmark for heating, ventilation, and air conditioning (HVAC) design.

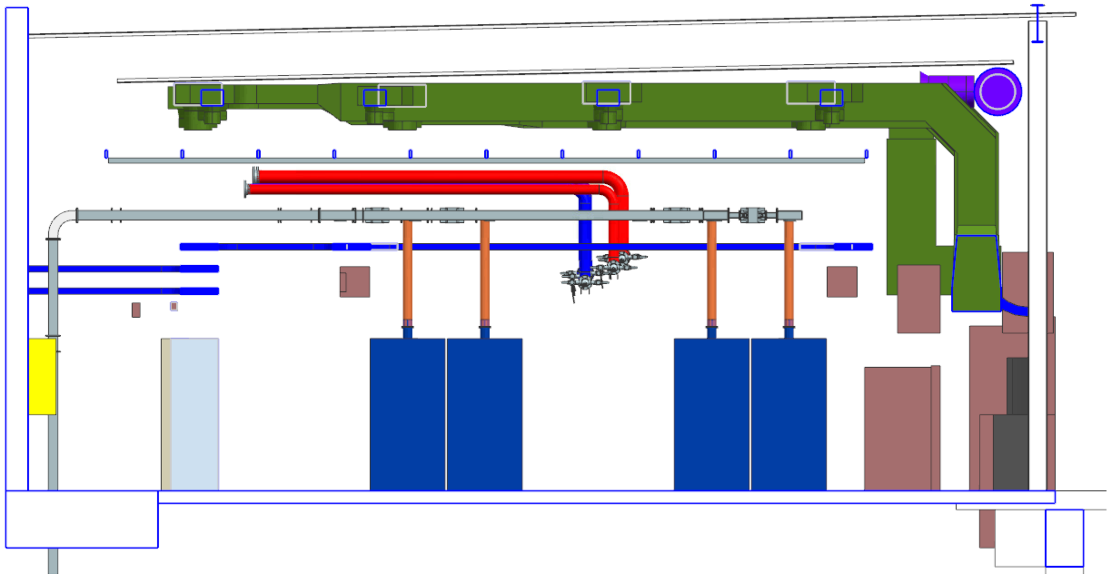

Figure 1: Cross-section of gallery building. HVAC in green, water in red and blue, conduit in grey, and power cabinets as blue rectangles.

System Configuration and Assumptions

The radio conduits each have a maximum input power and an attenuation factor associated with the signal frequency. For example, the highest-powered cryomodule designation, HB650, has a maximum power of 70 kW for each conduit and an attenuation factor of 0.148 dB/100’ (Mega Industries). This translates to 2.3 kW of power dissipated as heat in a 100-foot length of conduit. For this analysis, this attenuation was treated as uniform along the entire length. In reality, there would be more power dissipated near the source and less at the other end, but this different distribution would have a relatively small effect on the following calculations. Each signal was assumed to operate at maximum capacity continuously. This overestimates the total power in the system, as power levels will be individually varied as needed.

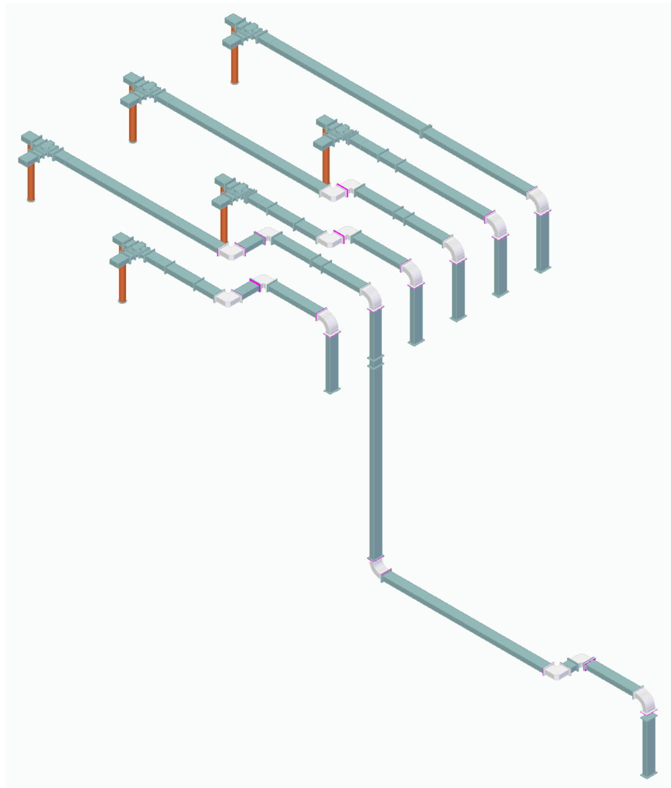

Figure 2: HB650 wave guide layout. All gallery sections shown, with one showing the full configuration. From top left to bottom right: free section, underground section, tunnel section.

There are two major components of each conduit line: a free section and an underground section. The free section will be in open air in the gallery building, which is to be maintained at 25°C, and is assumed to transfer heat by convection only, although there will be some conduction to support structures and attached machinery. The underground section will be buried in a metal outer casing, with stagnant air in between. This section was treated as conducting directly to surrounding soil, even thought it first transmits heat to its outer shell by convection and radiation. Soil was treated as an infinite, constant-temperature heat sink, which is a valid approximation at sufficient depths (Olgun). While the conduit will not be buried at quite such depths, this assumption is still reasonable and much more computationally efficient than accounting for variable surface temperatures. There is one more notable section of conduit in the accelerator tunnel, which is in open air controlled separately from the gallery. This section is relatively very short, meaning its contribution is small, and tunnel conditions are yet unknown to the RF group. The tunnel section was thus considered part of the free section.

Cooling water will be piped in by one network and out in another, roughly parallel network. For simplicity, these networks were treated as identical. Each network will be composed of metal piping with smaller polymer tubing branching off to and from each device. The tubing was disregarded, as its thermal conductivity and surface area are both significantly less than the metal pipes, making it a minor contributor.

The underground conduction model includes consideration of parallel conduit lines within the same cryomodule. Based on the observed interactions at that scale, no consideration was given to parallel conduits from different cryomodules. Convection models for both conduit and piping disregard interactions between nearby lines. This tends to overestimate power dissipation into air, adding a margin of safety. While no safety factor was specified for this work, one goal of simplifying and overestimating heat transfer was to build in some margin for errors, extreme circumstances, and general design tolerances.

Modeling Methodology

To begin, the underground segments of HB650 conduit were modeled using MATLAB. This model began with a singular conduit line passing through the soil, dissipating 452 kW of thermal energy. The rectangular conduit was approximated as a cylindrical conduit of equivalent surface area, to simplify near phenomena. As heat flux depends directly on surface area and only indirectly on specific geometry, this approximation is reasonable. With this simplification, heat flux at any point in the surrounding soil was solely a function of distance from the conduit. Such a correlation lends itself neatly to linearization. Two linear models were evaluated, each characterized by the assumed conducting surface geometry. A cylindrical model assumes heat transfer is exactly normal to the surface at all points, creating level curves parallel to the conduit. This is highly accurate in the theoretical case of an infinitely long conduit. In contrast, a spheroidal model assumes free ends, such that heat may travel outwards in the z direction, as well as radially. This results in level curves of decreasing eccentricity. While a spheroidal model can, with some effort, be used to determine phenomena at any point along the length of the conduit, it is most readily able to determine centerline behavior. Numerical models of both sorts were computed, showing convergence for distant phenomena but notable divergence at the surface of the conduit, which was of greatest concern.

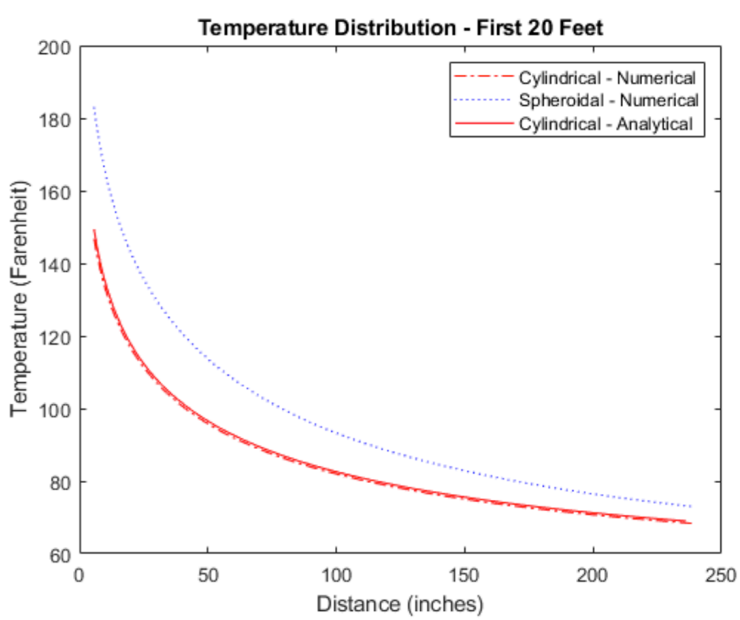

Figure 3: Temperature outputs of different conduction models.

Repeating calculations with two very similar models is often an inefficient use of time and computational power, so it was desirable to down-select to only one model for further analysis. The spheroidal model takes into account finite geometry, making it generally more accurate, but assumes free boundary conditions where the physical system will have constraints. Due to the relatively complex equations for the surface area of a spheroid, this model does not lend itself to investigation far from the center plane. The complexity of this calculation also limits this model to numerical approximation, which can require many small steps to reach high accuracy. A cylindrical model, however, can easily be determined analytically to investigate any given point with a single calculation. As it produces level curves parallel to the surface, it approximates average phenomena along the entire length of the conduit. In addition, the high aspect ratio of the conduit section (~20) suggests that an infinite-length approximation is valid. It is also worth note that, for lower dissipated power levels, the divergence between the two models decreased substantially. For these reasons, all further conduction models were based on cylindrical conducting surfaces.

Having determined an analytical model for phenomena around the underground section of one HB650 conduit line, it was deemed valuable that the interaction of parallel conduits be investigated. An HB650 cryomodule includes six parallel conduits, with equal spacing between. A total model of the soil was created by selecting a global coordinate system, assigning each conduit a ΔTemperaure curve centered at its location relative to coordinate zero, and adding the six conduit lines together. Conveniently, this model could be simplified to a set of material constants and average heat loss multiplied by a single logarithmic term involving the conduit radius, spacing between, and global position of the point to be evaluated. To determine actual temperature, the composite ΔTemperaure model was then added to the steady-state temperature of surrounding soil. At this point, the conduction model was complete and condensed to a single, modular equation.

The next step in analyzing the HB650 conduit lines was the development of a convection model for conduit segments in the air-conditioned gallery. While some segments may be directly under air conditioning vents, experiencing forced convection, the bulk of these conduits will be further removed, both spatially and by other devices breaking airflow, experiencing natural convection with largely stagnated air. Natural convection depends both on surface area and specific geometry, so no geometric simplification was permissible. Notably, natural convection depends on a characteristic length, which in this context can be determined as the ratio of surface area to surface perimeter. For rectangular conduits, perimeter was calculated as the sum of perimeters of each rectangular side; cylindrical conduit surfaces were "flattened" into equivalent rectangles with side lengths corresponding to the outer circumference and length of each conduit. Determination of convective heat transfer requires first determining an average convection coefficient, which itself is a function of geometry, surface temperature, and fluid temperature. The calculation is as follows: First, the density and viscosity of surrounding air were determined as a function of ambient and surface temperatures (Thermopedia). Heat capacity, thermal conductivity, and thermal expansion coefficients vary little in the range of 20-45 °C, which more than spans the expected range of film temperatures (approximate temperature of boundary flow). For this reason, and to reduce computational requirements, these three properties were held constant (NIST). The aforementioned five air properties, along with characteristic length, surface temperature, and ambient temperature, were then used to calculate the Prandtl, Grashof, and Rayleigh dimensionless groups for the flow. These three groups were then correlated with the flow's Nusselt number (Bright Hub Engineering). Finally, the Nusselt dimensionless group was solved for convection coefficient. Once this was determined, it could be used with the temperature difference and surface area to determine the total heat transfer. Using Microsoft Excel's GRG Nonlinear solver, surface temperature was varied until net heat flux reached zero, marking steady-state conditions for a completely air-cooled segment of conduit.

	A	B	C	D	E	F
1	Air Convection Calculator					
2						
3	Pipe Length	35	m	(approximate)		
4	Pipe Width	0.29845	m			
5	Pipe Height	0.1524	m			
6	Pipe Thickness	3.18E-03	m			
7	Air Temperature	25	C			
8	Surface Temperature	48.38526241	C			
9	Load	2692.749803	W	(loss in free sections)		
10						
11	Characteristic Length	0.447665875	m			
12	Density	1.183925153	kg/m^3		Prandlt #	0.703525
13	Viscosity	1.83741E-05	kg/m-s or N-s/m^2		Grashof #	2.91E+08
14	Heat Capacity	1007	J/kg-K		Rayleigh #	2.04E+08
15	Conductivity	0.0263	W/m-K		Nusselt #	6.21E+01
16	Expansion Coefficient	3.40E-03	/K			
17						
18	Convection Coefficient	3.65	W/m^2-K			
19						
20	Convection Area	31.5595	m^2			
21						
22	Power Dissipated	2692.749803	W	Net Flux	1.15502E-07	W

	A	B	C	D	E	F
1	Air Convection Calculator					
2						
3	Loss Rate (W/ft):		Temp Coefficient:			
4	23.45		-9.8971			
5						
6	Pipe Length	25	m	(approximate)		
7	Pipe Width	0.29845	m			
8	Pipe Height	0.1524	m			
9	Pipe	3.18E-03	m			
10	Air Temperature	25	C			
11	Surface Temperature	51.47862235	C	(average, heat effected zone)		
12	Dissipated Power	324.0044581	W	(from penetration to free sections)		
13	Preload	1923.392388	W	(loss in free sections)		
14						
15	Characteristic Length	0.446405735	m			
16	Density	1.183925153	kg/m^3		Prandlt #	0.703525
17	Viscosity	1.83741E-05	kg/m-s or N-s/m^2		Grashof #	3.26E+08
18	Heat Capacity	1007	J/kg-K		Rayleigh #	2.29E+08
19	Conductivity	0.0263	W/m-K		Nusselt #	6.39E+01
20	Expansion Coefficient	3.40E-03	/K			
21						
22	Convection Coefficient	3.77	W/m^2-K			
23						
24	Convection Area	22.5425	m^2			
25						
26	Total Power Dissipated	2247.396828	W	Flux Differ	1.904E-05	W
27						
28	Soil Temperature	51.47862235	C	Temp Diffe	-4.33431E-13	C
29		124.6615202	F			

Figure 4: Convection calculator with (right) and without (left) integrated conduction model.

At this point, there were two completely separate models: an analytical model for conduction and an iterative model for convection. The final step in analyzing the HB650 conduit lines, and all others, was to combine these two models. This was done by adding only a few extra considerations to the convection model. First, a second independent variable was added, that being the heat flux between the free section and the buried section. Next, the equation for soil temperature from the conduction model was included, representing the surface temperature of the underground segment. The equation was slightly changed to reflect the varying heat transfer into the free section rather than surrounding soil. Because this is a physical system, with continuity between free and underground sections, the surface temperatures of these sections must be equal at some point in space. The combined heat transfer model solves for a combination of free surface temperature and heat flux from the underground segment such that net flux is zero (steady state) and surface temperatures are equal (continuity). This combined model was used to analyze each unique conduit line to determine its expected peak temperature and heat transfer to air.

Finally, the cooling water circulation system was simplified to a worse-than-worst-case approximation, both to provide an extra safety margin and to make it readily compatible with the convection model used for conduit lines. Supply lines were all assumed to be one constant temperature, and return lines another. This is equivalent to a very high flow rate within the pipes, whereas a more realistic model would include gradual temperature drops as water travels along the network, losing energy. With constant surface temperatures, the convection model can be simplified, relying only on pipe geometry and directly solving for heat flux, with no iteration necessary. This analysis was carried out on all unique water pipes to determine expected heat transfer to air.

Results and Recommendations

As shown in Table 1, the peak conduit surface temperatures range from 99-125°F. The upper limit of this range, while still within the manufacturer operating range of 95-158°F (Mega Industries), is just hot enough to cause 1st-degree burns if in contact with skin. The current configuration, then, is safe for the hardware but not for human operators. It would be of value to the lab to add some sort of barrier, at least around HB650 conduits, to prevent direct contact while in use. This could be as simple and inexpensive as a chicken wire cage around the area.

Table 1: Conduit Peak Temperatures

Cryomodule	HWR	SSR1	SSR2	LB650	HB650
Peak Surface Temperature (°F)	118	99	111	106	125

Table 2: Distribution Losses to Gallery Air

Distribution Group	HWR	SSR1	SSR2	LB650	HB650	Water	**Total**
Power Dissipation (kW)	3.54	2.62	3.46	4.93	13.44	18.46	**176.45**

Maximum power dissipation values are shown in Table 2 for each unique group of distribution lines, as well as totals for all distribution lines in the gallery, which includes multiple of each cryomodule. During an intermediate review, it was stated that the conduit totals were as expected and the remaining cooling power was approximately 100 kW. Even with the intentional overestimation, the water system will consume only a fraction of this power. The current HVAC system design is therefore comfortably capable of meeting requirements. Further, if it is run at or near full capacity, it may be able to lower the HB650 conduits to a safer temperature.

Finally, it must be noted that all cryomodules are not expected to simultaneously operate at full capacity for prolonged periods of time. More realistic conditions would result in both lower heat flux and higher excess cooling power. Together, these factors may further cool conduits to the point of not requiring any additional safety measures. However, such a conclusion would require further analysis based on a better understanding of day-to-day operations.

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