Fermilab

Particle Physics Division

Mechanical Department Engineering Note

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Project Internal Reference:

Project: CMS Upgrade Cooling System Test Design

Title: CO2 Cooling System – Design Elements

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Abstract Summary:

Key CO2 cooling system design elements and the thoughts behind them are documented here.

BACKGROUND

The purpose of the CMS upgrade cooling system test design is to demonstrate CO2 cooling and provide a cooling system that can be used to test detectors at Fermilab.

Design Parameters

A. ***Deliver saturated or slightly sub-cooled CO2 to detector***

B. ***Ability to handle 15-60 psi detector pressure drops***

C. ***Ability to handle any vapor quality at the detector outlet***

D. ***Capacity to handle up to 5 kW heat load***

E. ***Ability to provide liquid CO2 at -30 °C to +15 °C***

F. ***CO2 quality at detector outlet of 25%, maximum***

G. ***CO2 side, design pressure of 1200 psig***

DESIGN ELEMENTS

Listed here are design features identified during CO2 cooling system design and P&ID development.

I. Closed CO2 Cooling Loop

The CO2 cooling will be closed loop. A tank will be used to hold an inventory of liquid CO2 to handle the loop needs. Since it is closed loop, the system pressure will be highest when the system is turned off and the CO2 reaches ambient temperature. At 30 °C the CO2 equilibrium pressure is 1031.6 psig. The design pressure of 1200 psig provides a margin of safety. Any equipment that is wetted by the CO2 must have a design pressure of 1200 psig.

II. CO2 Pump

To provide 5 kW of cooling takes less than a gallon per minute of liquid CO_2 @ -30 °C and an outlet vapor quality of 25%. Combining this with the detector pressure drop of 60 psi results in an application for a low flow / high head pump that has a design casing pressure of 1200 psig.

A small commercially available seal-less turbine pump was found for this application. The pump manufacturer, Warrender makes seal-less mag-drive turbine pumps for low flow / high head applications and for liquid CO_2 service.

III. Passive Phase Separator

To have only liquid CO_2 going to the detector requires separation of any CO_2 vapor generated by heat from pumping and from environmental heat leakage. This can be handled by a phase separator.

Recirculation of some liquid CO_2 with the CO_2 vapor keeps the phase separator simple. No active controls are required on the phase separator if the recirculated liquid CO_2 is high enough to cover all operating scenarios. An orifice sized for liquid with maximum 10% vapor will provide this flow.

IV. CO2 Flow Control

The flow of CO_2 to the detector can be measured after the phase separator. Putting the CO_2 pump motor on a speed controller (variable frequency drive) provides the control point to achieve a target CO_2 flow rate into the detector.

V. Detector Outlet Monitoring

The successful operation of the detector micro tubes depends on the having excess liquid CO_2 to protect against burn out and hot spots. The target detector outlet vapor quality is 25%. The actual vapor quality at any point in time will depend on the number of detectors operating and the CO_2 temperature.

A weir flow meter on the detector outlet can be used to provide a measure of the liquid CO_2 out flow without adding significant pressure drop.

VI. Keep the CO2 Dry

Ice and/or carbonic acid will form if the water concentration reaches a level above the solubility limit in liquid CO_2. Ice can plug small channels and carbonic acid is corrosive. Controlling the water content in the CO_2 is critical.

Molecular sieves (zeolites) type inline dryer are used in commercial CO_2 refrigeration systems to control the water content. Blend type filters with activated alumina are not necessary since there is no free acid to absorb if the water content is kept low.

Molecular sieves are available in cartridge form for commercial CO_2 refrigerant drying. The commercially available housing is rated to only 650 psig. A custom housing will have to be fabricated with a 1200 psig design pressure. The commercially available cartridge can then be used in this housing.

VII. Pressure Controlled CO2 Refrigeration

The pressure of the CO_2 supply tank can be used as an indication of CO_2 temperature through the saturation pressure / temperature relationship for CO_2. The CO_2 tank pressure can then be used as the control to turn the refrigeration ON/OFF to maintain the CO_2 temperature (pressure).

VIII. CO2 Condenser

Heat will be removed from the CO_2 tank by CO_2 condensers. The CO_2 wetted components will be stainless steel for corrosion resistance. Corrosion would produce exchanger fouling and reduce condenser capacity.

The cooling fluid to the CO_2 condenser will be commercial refrigerant.

IX. Commercial Refrigeration Units

Mechanical refrigeration condensers will be used to cool the CO_2 reservoir. These will be commercial, off the shelf units, capable of providing refrigerant to the CO_2 condenser at -40 °C. Use of commercial packages provides proven refrigeration technology at reasonable cost using 404A.

Three refrigeration condenser units will be used. This will provide three step changes in capacity. Evaluation of capacity versus temperature will be used to determine the sizing and staging of the three refrigeration units.

X. Electric CO2 Tank Heater

An electric heater will be used to heat to the CO_2 tank. This heater will provide a trim control in holding a particular CO_2 coolant temperature. This heat exchanger would be used in conjunction with the three condenser units. The sizing of the electric heater will be done as part of the capacity versus temperature evaluation identified in section IX.

XI. Liquid-Suction Refrigerant Heat Exchange

Heat exchange can be done between the liquid and suction side of commercial refrigeration equipment to increase system performance. This method of increasing performance puts a greater heat load on the refrigerant condenser and decreases compressor capacity due to the decreased suction density.

For packaged refrigeration units the amount of liquid-suction heat exchange will be limited by the vendors design. This is not a required design feature and will not be used a selection or design criteria. Liquid-suction heat exchange will be used if available for a given vendor package.

Heat and Material Balance

A simple heat and material balance EXCEL model was built based on the design parameters above and the vendor supplied pump characteristics for the Warrender turbine pump.

The material balance is based on a CO2 quality at the detector outlet of 10% which results in a more conservative design. Operating at a vapor quality of 25% at the outlet lowers the CO2 flow required and lowers the total heat to be removed.

Depending on the pressure and flow, the pump can do significant work and this is included as a heat of pumping. The pump curve is built into the model and the heat of pump varies accordingly.

The heat and material balance results for the combinations of design parameters are summarized in table 1.

Figure 1 shows a simple representation of the CO2 cooling system at the combination of design parameters that fixes the size of the vent orifice on the phase separator.

TABLE 1: CO2 Cooling System Scenarios

T (deg. C)	P (PSIG)	Detector Heat load (KW)	design press diff.(PSI)	flow to detect. (gpm)	flow from pump (gpm)	pump speed (rpm)	pump power (KW)	**Total Heat load (KW)**	CO2 liq dens. (lb/ft^3)	CO2 heat of vap. (BTU/lb)
@ 15 psi pressure differential at 1, 3, 5 kW Load										
-30.0	192.38	1.0	15.0	0.5	1.2	754	0.14	**1.1**	67.2	130.6
-30.0	192.38	3.0	15.0	1.5	2.2	781	0.15	**3.2**	67.2	130.6
-30.0	192.38	5.0	15.0	2.4	3.2	812	0.16	**5.2**	67.2	130.6
15.0	723.13	1.0	15.0	1.1	1.9	774	0.15	**1.2**	51.3	76.0
15.0	723.13	3.0	15.0	3.3	4.1	846	0.18	**3.2**	51.3	76.0
15.0	723.13	5.0	15.0	5.5	6.3	943	0.23	**5.2**	51.3	76.0
@ 30 psi pressure differential at 1, 3, 5 kW Load										
-30.0	192.38	1.0	30.0	0.5	1.5	1061	0.40	**1.4**	67.2	130.6
-30.0	192.38	3.0	30.0	1.5	2.5	1087	0.42	**3.4**	67.2	130.6
-30.0	192.38	5.0	30.0	2.4	3.5	1116	0.44	**5.4**	67.2	130.6
15.0	723.13	1.0	30.0	1.1	2.3	1081	0.42	**1.4**	51.3	76.0
15.0	723.13	3.0	30.0	3.3	4.5	1148	0.47	**3.5**	51.3	76.0
15.0	723.13	5.0	30.0	5.5	6.7	1228	0.54	**5.5**	51.3	76.0
[redacted]										
-30.0	192.38	1.0	60.0	0.5	2.0	1495	1.13	**2.1**	67.2	130.6
-30.0	192.38	3.0	60.0	1.5	2.9	1521	1.17	**4.2**	67.2	130.6
-30.0	192.38	5.0	60.0	2.4	3.9	1548	1.20	**6.2**	67.2	130.6
15.0	723.13	1.0	60.0	1.1	2.8	1516	1.16	**2.2**	51.3	76.0
15.0	723.13	3.0	60.0	3.3	5.0	1580	1.25	**4.2**	51.3	76.0
15.0	723.13	5.0	60.0	5.5	7.1	1651	1.36	**6.4**	51.3	76.0
Flow to detector closed, @ minimum pump speed										
-30.0	192.38	0.0	15.5	0.0	0.8	754	0.15	**0.15**	67.2	130.6
15.0	723.13	0.0	15.4	0.0	0.9	754	0.15	**0.15**	51.3	76.0
Flow to detector closed, @ full pump speed										
-30.0	192.38	0.0	84.5	0.0	1.7	1759	1.87	**1.9**	67.2	130.6
15.0	723.13	0.0	84.0	0.0	2.0	1760	1.86	**1.9**	51.3	76.0

CMS CO2 COOLING - Simple Mass and Energy Balance

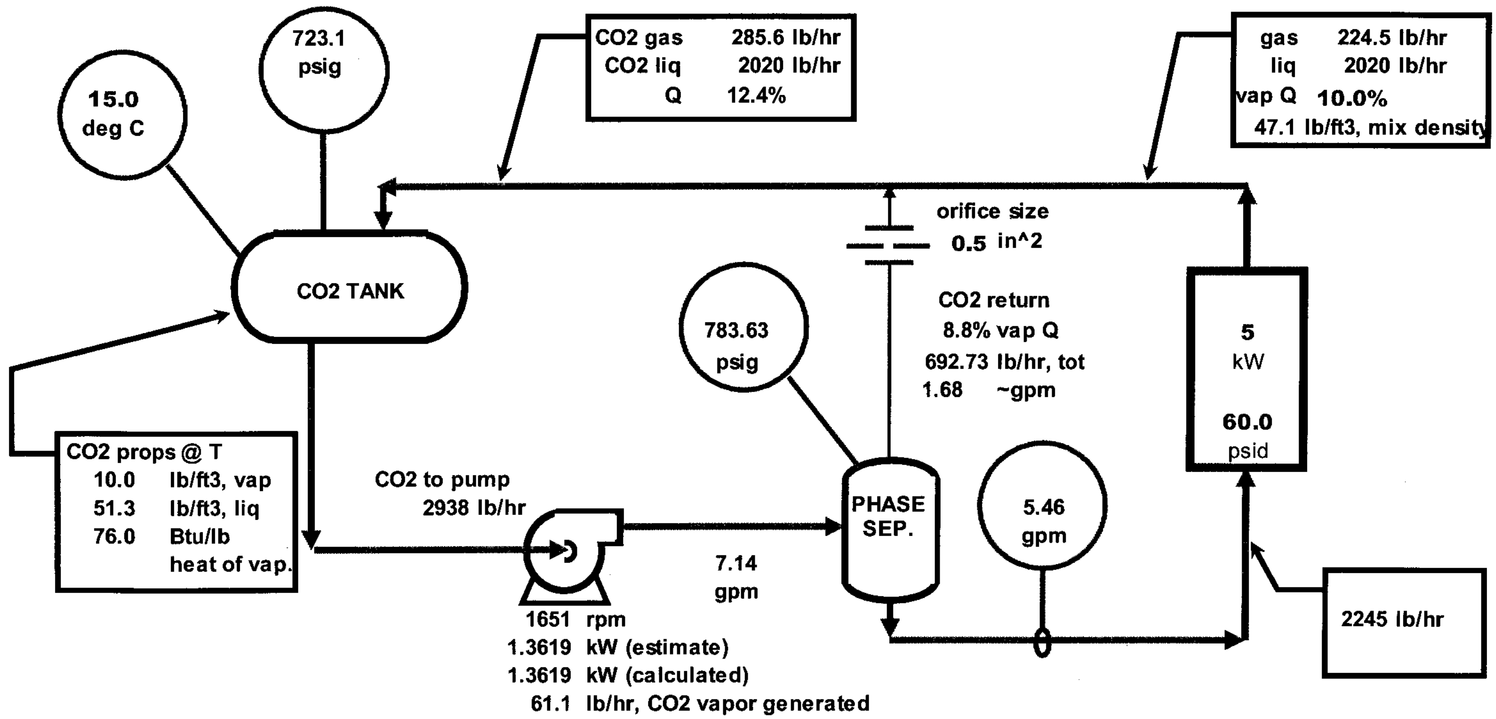

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FIGURE 1