APD Drier Conceptual Design Proposal

Erik Voirin – evoirin@fnal.gov – 630-840-5168

Scope of Specific Problem

The APDs on the NOvA detector are experiencing damage from moisture from surrounding air. The APDs are held at -15°C, which is much lower than the dew point in most environments and it is not possible to dehumidify air below around 5°C using a conventional condensing dehumidifier. Even with a correctly seated O-ring, water can permeate through the O-rings, fittings, hoses, other plastic/rubber system components and damage the APDs.

Information on Condensation/Dewpoint/Frostpoint:

Condensation or Deposition (vapor changing to solid) of water vapor on a surface happens when that surface temperature is lower than the saturation temperature corresponding to the partial pressure of water vapor in the environment. One lowers the dew point in an environment by reducing the partial pressure of water in the air. This can be done by taking water out of the air by condensing dehumidifiers or by using desiccant dehumidification which can lower the dew-point to -40°C.

Solution Methods:

Three drying systems were considered and are discussed here. One being a system which flows dry air into each APD enclosure and out the other side. The second being a vacuum system which continuously pumps on the APD enclosures, drying them out. The third, and recommended type, being a pressurized system which purges manifolds and relies on the molecular conductance of water vapor in air to dry the APD enclosures.

Option 1: flow through system

Flowing a large amount of dry air or nitrogen over the cold APD surface would surely prevent condensation/frosting, but this would require two holes in each APD housing for an inlet and outlet. This method may also raise the heat load seen by the TEC substantially, putting more load on the TECs and the water cooling system, and increase the water temperature rise across the groups of TECs in series disrupting the TEC controllers.

Option 2: Vacuum System

Another way of lowering the partial pressure of water in an environment is by lowering the absolute pressure of the environment itself. Calculations show if we take ambient air at 25°C with a 10°C dew point (80% Relative Humidity) and lower the pressure down to ~0.78 psia, we also lower the partial pressure of water low enough to produce a new dew point (frost point at this temperature) of -17°C, which is the temperature of the APD cold side. If we pull this partial vacuum on the APDs enclosures, we prevent condensation and frosting, and we only need 1 hole per APD enclosure. Unfortunately this would require somewhat large pipes due to the difficulty in pumping a low pressure (high specific volume) fluid.

Option 3: dry purged manifold conductance system

This system works by providing a dry manifold in which dry gas in continuously purged and exits out the end. APD enclosures are connected to this manifold by short hoses. Any water vapor which permeates into the APD enclosures or connecting offshoot tube will be drawn into the manifold by molecular diffusion and purged out the end. In using this drying method the connecting tubes must be quite short as the difference in water concentration is directly proportional to the length of these tubes. The pressure in the manifold should also be kept as low as possible since the molecular diffusion rate is inversely proportional to absolute pressure. Detailed calculation were performed which show the APDs and manifold may be connected in 24 rows, each running North the entire length of the detector, 480 in a row of 15 Di-Blocks. Calculations show 1/8" tube will suffice for the manifolds and offshoot hoses if the permeation through the hose is less than 0.1 gm*mm/m2*day*kPa and the offshoot hoses are 2 inches long or less. Shorter offshoot hoses or larger diameter offshoot hoses or manifolds would increase the factor of safety of the system. Lower permeation hoses would also aid in system performance, as well as running less APDs on each manifold, perhaps a central manifold on Di-block #7 with tubes which run both North and South from there; though the system must at first be installed at the south end as it must work with 1-15 di-blocks as the detector is built and run as each Di-block is installed.

Design Conditions:

- Design Dryness:
    - Dewpoint: -25°C
    - Water concentration: 0.552 gm/m³
- Ambient Conditions:
    - Temperature: 25°C
    - Relative Humidity: 90%
    - Atmospheric pressure: 14 psia
- Water Transport into each APD
    - 17.5 micrograms/day (Five times the specification by Mat Muether)
- Dry Air Supply
    - Dewpoint: -40°C
    - Water concentration: 0.121 gm/m³

System and Calculation Overview:

A piping and instrumentation diagram is shown in Figure 1, which includes the compressors and air driers as well as backup nitrogen which will automatically takeover in case of failure of the main drier system. The tees and hoses which make up the manifold and offshoot hoses are shown in Figure 2; these must be tested for solid fitment and permeation rates.

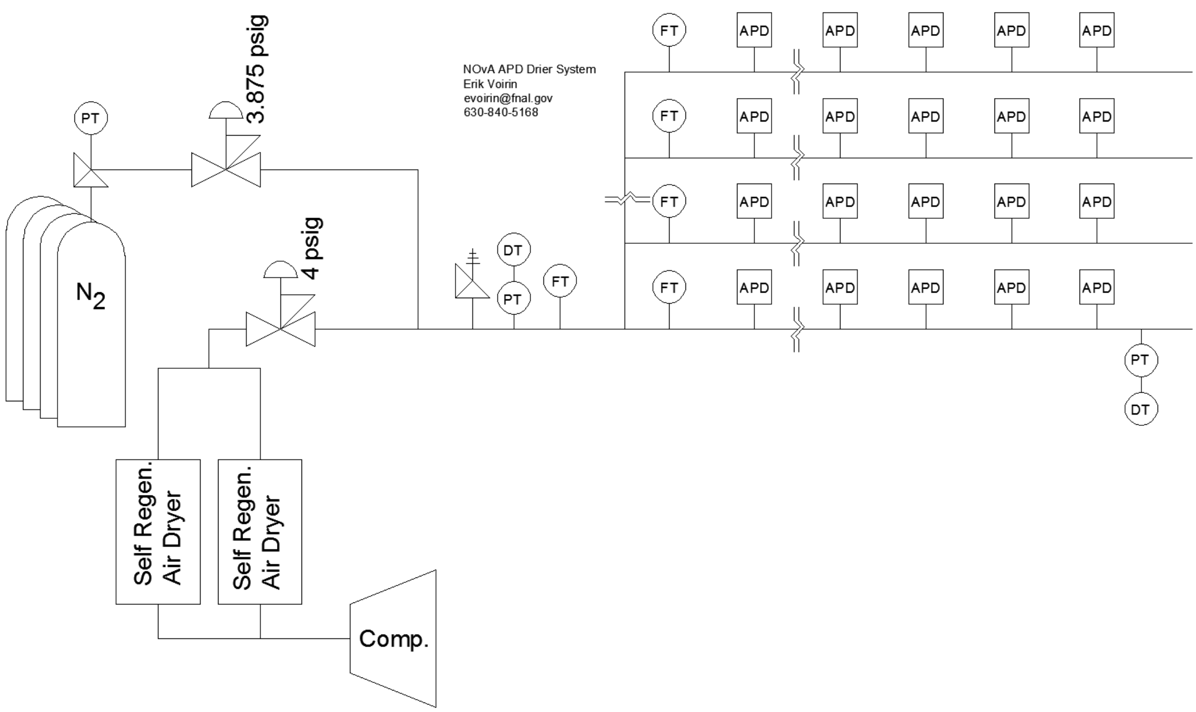


Figure 1: Piping and Instrumentation Diagram.

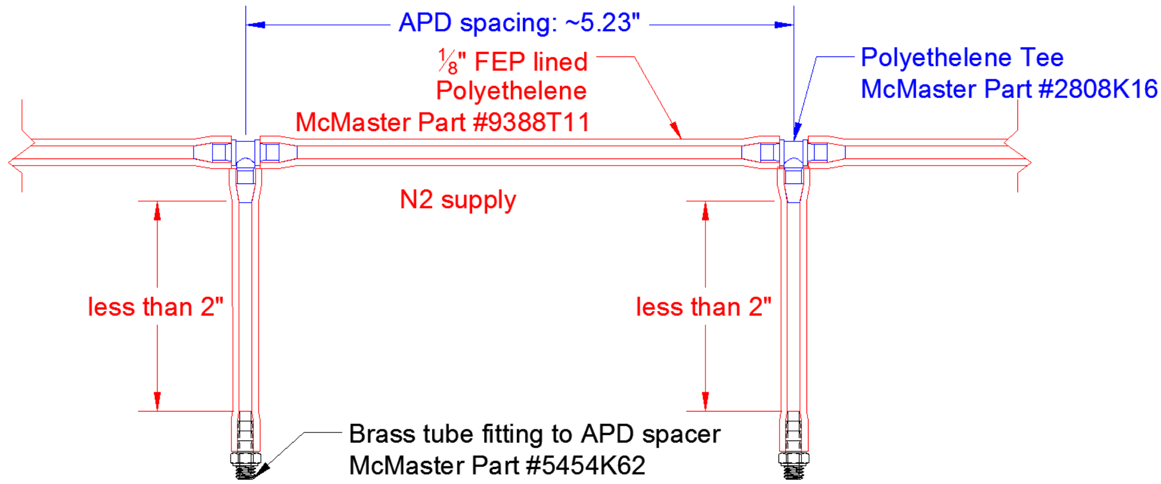


Figure 2: Proposed parts for manifold and tubing connections

Figure 3 shows the Dewpoint at each of the 480 tees and APDs in each row; the APD water concentration is somewhat consistant throughout the line regardless of the buildup of water in the manifold due to the pressure drop of the flow decreasing absolute pressure and increasing molecular diffusion rates. This is with 4psi at the beginning of the line, which corresponds to a flow rate of 4.375 SCFH through each manifold. These calculations also take into account all flow which would leak out of the APDs according to the leak specification of "10 inHg/hr @ 25inHg vacuum" and assume all water must exit through the manifold outlets, not taking advantage of water exiting through any APD leaks.

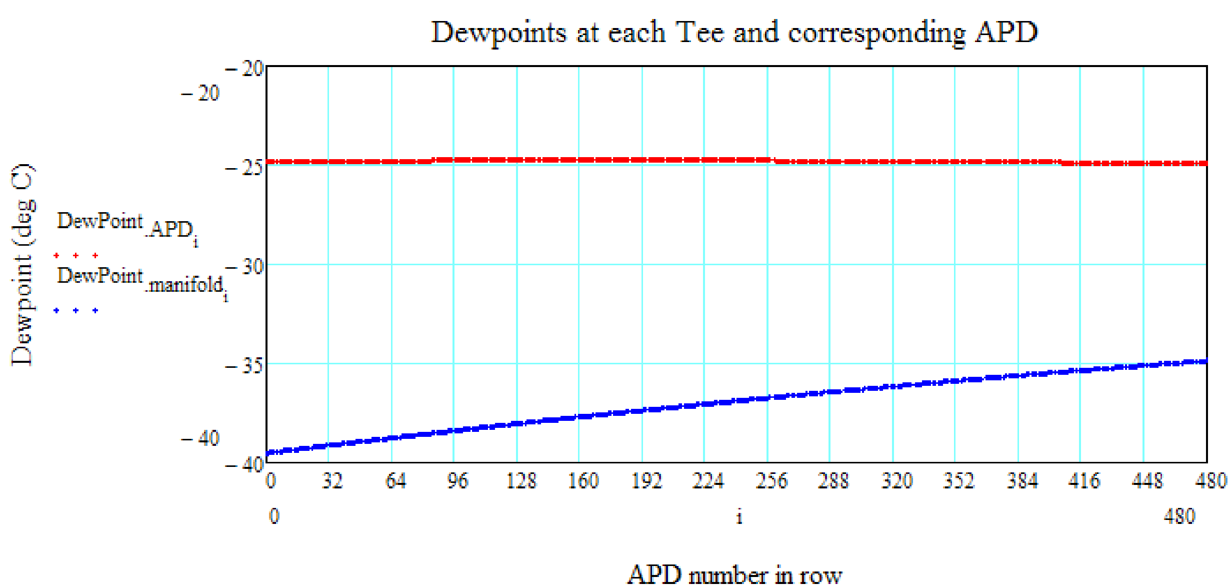


Figure 3: Dewpoints along manifold and corresponding APD enclosure.

APPENDIX A
Detailed Design Calculations and Analyses

Calculations for pressurized APD drier system

Erik Voirin - evoirin@fnal.gov - 630-840-5168
Fermilab PPD - Fluid and Thermal Engineering

Gas Properties and Dewpoint Data

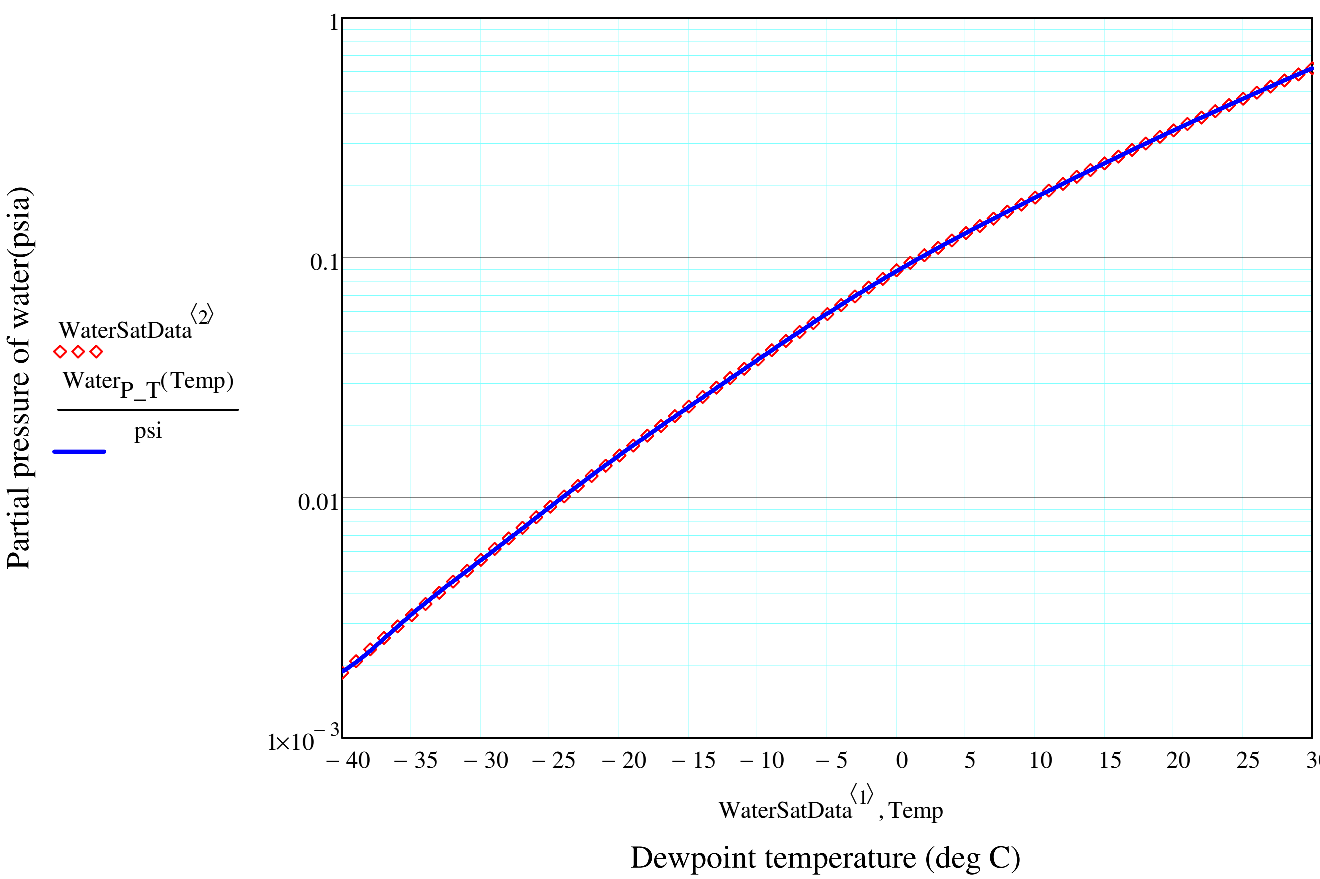
Dewpoint Data Curve fits

$$Water_{P\_T}(Temp) := interp\left(regress\left(WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 2\rangle}, 12\right), WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 2\rangle}, Temp\right)\cdot psi$$

$$Water_{\rho\_T}(Temp) := interp\left(regress\left(WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 3\rangle}, 12\right), WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 3\rangle}, Temp\right)\cdot \frac{kg}{m^3}$$

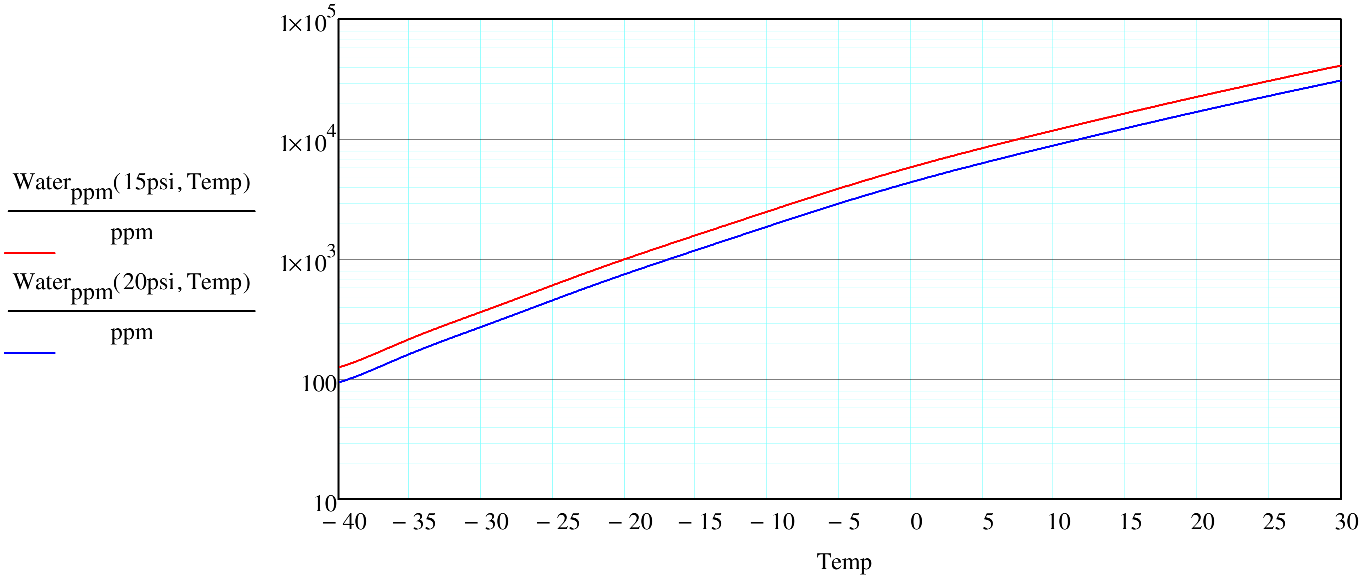
$$Water_{\rho\_P}(press) := interp\left(regress\left(WaterSatData^{\langle 2\rangle}, WaterSatData^{\langle 3\rangle}, 12\right), WaterSatData^{\langle 2\rangle}, WaterSatData^{\langle 3\rangle}, press\right)\cdot \frac{kg}{m^3}$$

$$DewPoint_{T\_\rho}(Dens) := interp\left(regress\left(WaterSatData^{\langle 3\rangle}, WaterSatData^{\langle 1\rangle}, 20\right), WaterSatData^{\langle 3\rangle}, WaterSatData^{\langle 1\rangle}, Dens\right)$$



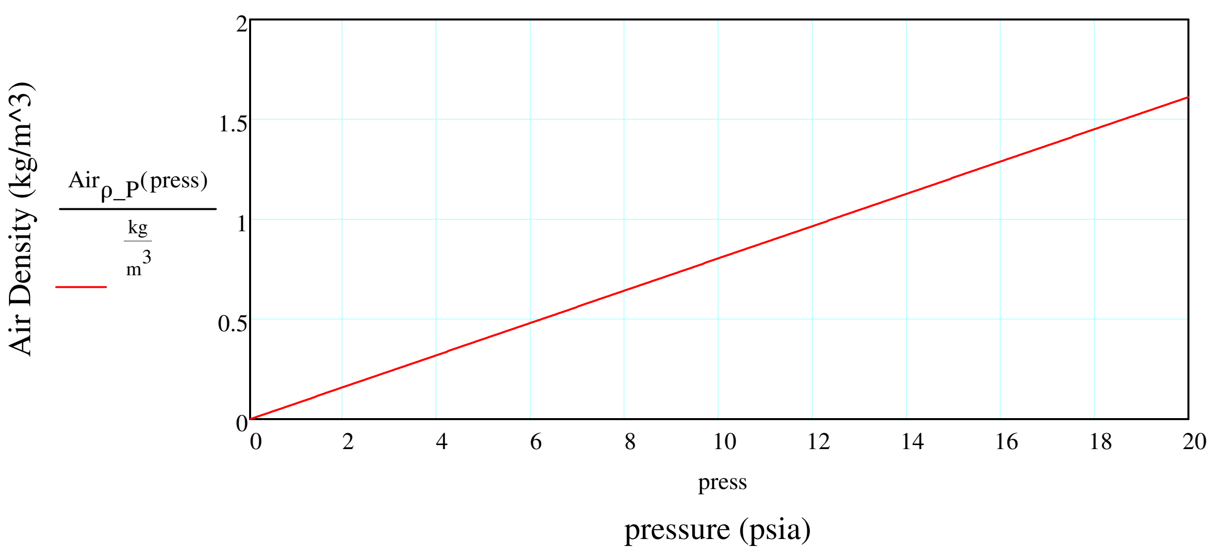
Function for water ppm with respect to static pressure and dewpoint temperature

$$Water_{ppm}(press, Temp) := \frac{Water_{P\_T}(Temp)}{press}$$



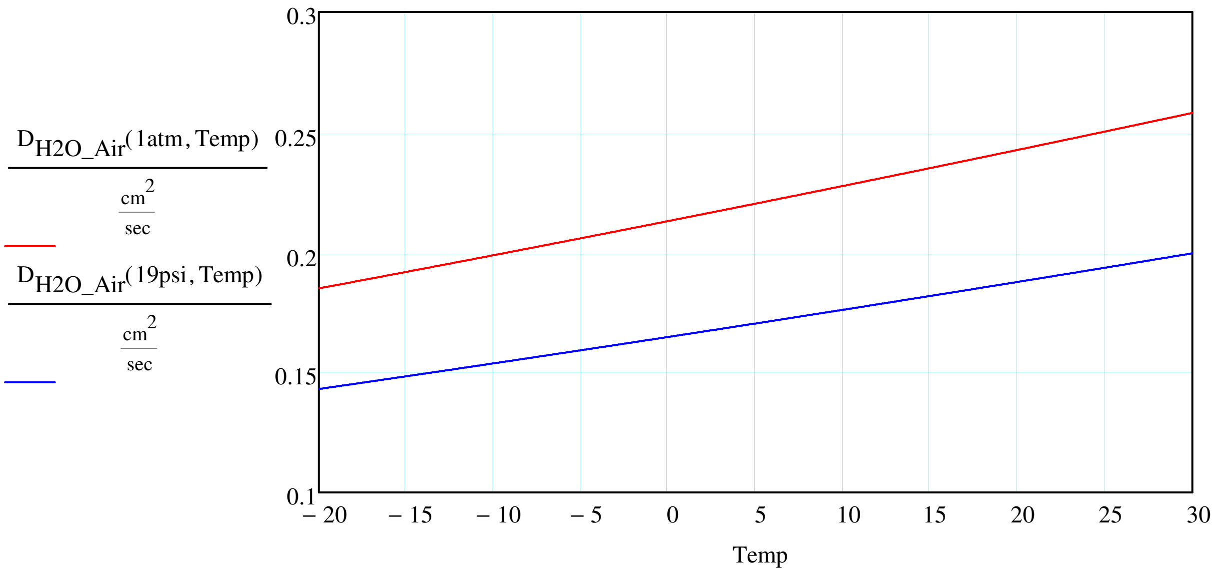
Air Data (density with respect to static pressure)

$$Air_{\rho\_P}(press) := interp\left(regress\left(AirDensityData^{\langle 1\rangle}, AirDensityData^{\langle 2\rangle}, 2\right), AirDensityData^{\langle 1\rangle}, AirDensityData^{\langle 2\rangle}, press\right)\cdot\frac{kg}{m^3}$$



Mass diffusion coefficient of Water Vapor in air WRT temperature and pressure

$$D_{H2O\_Air}(Press, Temp) := interp\left(regress\left(Diff_{Data}^{\langle 1 \rangle}, Diff_{Data}^{\langle 2 \rangle}, 4\right), Diff_{Data}^{\langle 1 \rangle}, Diff_{Data}^{\langle 2 \rangle}, Temp\right) \cdot \frac{cm^2}{sec} \cdot \frac{1atm}{Press}$$



System and Site Specifications and Requirements

Number of APDs which need to be dried

$num_{row} := 24$ $num_{inRow} := 32$ $num_{DB} := 15$ $num_{APDs} := num_{row} \cdot num_{inRow} \cdot num_{DB} = 11520$

Specifications say APD enclosure must be drier than dewpoint of -25C

$Dewpoint_{Design} := -25$

Partial pressure and density of water at design dewpoint

$Water_{P\_T}\left(Dewpoint_{Design}\right) = 0.009 \cdot psi$ $Water_{\rho\_T}\left(Dewpoint_{Design}\right) = 0.552 \cdot \frac{gm}{m^3}$ $Water_{\rho\_T}(-15) = 1.383 \cdot \frac{gm}{m^3}$

That puts us at 40% of the water content of a dew point of -15C

$$\frac{Water_{\rho\_T}\left(Dewpoint_{Design}\right)}{Water_{\rho\_T}(-15)} = 40 \cdot \%$$

Determine Dry Air Flow Needed

Partial Pressure of water at 25C and 90% relative humidity

$ExitWaterContent := 25\%$ *(of dewpoint design)*

$Relative_{Humidity} := 90\%$ *(ambient)*

$Ambient_{water} := Water_{P\_T}(25)\left(Relative_{Humidity}\right) = 2852.112\,Pa$

Atmospheric pressure at NOvA site (elevation at detector bottom ~370m)

$P_{NOvA} := 14psi$

Flow of dry air will be supplied at 5 psig

$Air_{pressure} := P_{NOvA} + 4psi$

Water permeation through APD per NOvA doc-5550

$Water_{PermeationData} := 3.5\frac{\mu g}{day}$

Design Permeation Rate (multiply by 5 for conservative approach)

$Water_{PermeationPerAPD} := Water_{PermeationData} \cdot 5 = 17.5 \cdot \frac{\mu g}{day}$

$Water_{Permeation\_APDseal} := Water_{PermeationPerAPD} \cdot num_{APDs} = 0.202 \cdot \frac{gm}{day}$

Quick Reality Check on these measurements

$Rel_{Hum} := 90\%$

guesses on seal size....

$Flux\left(t_{seal}\right) := \frac{0.42}{\frac{t_{seal}}{mil}} \cdot \frac{gm}{100in^2 \cdot 24hr} \cdot Rel_{Hum}$ $A_{seal} := 0.01in \cdot \pi \cdot 1in \cdot 3$ $t_{Seal} := 0.035in$

$FluxCalculated := Flux\left(t_{Seal}\right) \cdot A_{seal} = 10.179 \cdot \frac{\mu g}{day}$ *Realistic measurement*

Calculate air supply needed to dry this vapor flow into the system

$$APD_{PermFlowNeeded} := \frac{Water_{Permeation\_APDseal}}{Water_{\rho\_T}\left(Dewpoint_{Design}\right)(ExitWaterContent)} = 2.15\cdot\frac{ft^3}{hr}$$

$$APD_{PermFlowNeeded} := APD_{PermFlowNeeded}\cdot\left(\frac{Air_{\rho\_P}\left(\frac{Air_{pressure}}{psi}\right)}{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)}\right) = 2.634\cdot SCFH$$

Permeation of water through the hose, (this will be tested, as permeation sources are scarce. Current design will be a polyethylene hose, or perhaps an FEP lines polyethylene hose

Size of hose:

$ID_{hose} := 0.125in$ $OD_{hose} := 0.25in$

$$Area_{hose} := \pi\cdot\frac{\left(ID_{hose} + OD_{hose}\right)}{2} \qquad t_{hose} := \frac{OD_{hose} - ID_{hose}}{2}$$

Water permeation estimate for LDPE, estimate from several sources, though not all are consistent, which is why we will test the actual hose we purchase as well as the fittings.

$$Perm_{hose} := 0.1\frac{gm\cdot mm}{day\cdot m^2\cdot kPa}$$

Low hose permeation is of vital importance to the system drying properly

How much hose is in the system?

$APD_{pitch} := 5.25in$ $Length_{Detector} := APD_{pitch}\cdot 32\cdot 15 = 210\cdot ft$

$Length_{offshoot} := 2in$

$$Length_{hose} := 24\cdot Length_{Detector} + 11520\cdot Length_{offshoot} = 6960\cdot ft$$

We must calculate the total water permeation into the system to determine how much total dry air flow we will need

$$mass_{intoHosePerLength} := \frac{Perm_{hose} \cdot Area_{hose} \cdot Ambient_{water}}{t_{hose}} = 0.112 \cdot \frac{mg}{m \cdot hr}$$

$$mass_{intoAllHose} := mass_{intoHosePerLength} \cdot Length_{hose} = 5.702 \cdot \frac{gm}{day}$$

$$HoseFlowNeeded := \frac{mass_{intoAllHose}}{Water_{\rho\_T}\left(Dewpoint_{Design}\right)(ExitWaterContent)} = 60.814 \cdot \frac{ft^3}{hr}$$

$$HoseFlowNeeded_{STP} := HoseFlowNeeded \cdot \left(\frac{Air_{\rho\_P}\left(\frac{Air_{pressure}}{psi}\right)}{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)} \right) = 74.493 \cdot SCFH$$

Laminar leak rates from discussion with Mat Muether (25inHg vacuum test)

$$Laminar_{LeakTypical} := 1 \frac{inHg}{hr} \qquad Laminar_{LeakLarge} := 10 \frac{inHg}{hr}$$

$$d_{tubetest} := 0.25in \qquad l_{tubetest} := 1ft$$

$$Vol_{tubetest} := \frac{\pi}{4} \cdot d_{tubetest}^{\;2} \cdot l_{tubetest} \qquad Vol_{APD} := 4.3mL$$

$$VolAPDtest := Vol_{APD} + Vol_{tubetest} = 13.953 \cdot mL$$

$$DP_{test} := 25inHg \qquad P_{test} := 14.4psi - DP_{test} = 2.117 \cdot psi$$

$$mass_{changeTypical} := \frac{\left(Air_{\rho\_P}\left(\frac{P_{test} + Laminar_{LeakTypical} \cdot hr}{psi}\right) - Air_{\rho\_P}\left(\frac{P_{test}}{psi}\right)\right) \cdot VolAPDtest}{hr \cdot DP_{test}} = 44.967 \cdot \frac{\mu g}{hr \cdot psi}$$

$$mass_{changeLarge} := \frac{\left(Air_{\rho\_P}\left(\frac{P_{test} + Laminar_{LeakLarge} \cdot hr}{psi}\right) - Air_{\rho\_P}\left(\frac{P_{test}}{psi}\right)\right) \cdot VolAPDtest}{hr \cdot DP_{test}} = 449.713 \cdot \frac{\mu g}{hr \cdot psi}$$

$$Leak_{flowNeeded} := mass_{changeLarge} \cdot num_{APDs} \cdot \left(Air_{pressure} - P_{NOvA}\right) = 20.723 \cdot \frac{gm}{hr}$$

$APD_{flowLeak}(Air_{pressure}) := mass_{changeLarge} \cdot (Air_{pressure} - P_{NOvA})$ *for later program*

$$Vol_{flowLeakSTP} := \frac{Leak_{flowNeeded}}{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)} = 0.618 \cdot SCFH$$

$$SystemFlow := Vol_{flowLeakSTP} + HoseFlowNeeded_{STP} + APD_{PermFlowNeeded} = 77.744 \cdot SCFH$$

$$SystemFlow = 1.296 \cdot SCFM$$

Water will be permeating through the seals regardless of the higher pressure inside due to the partial pressure difference of the water. All this water should be carried away to an outlet and the partial pressure and related density of water vapor in the manifold should never exceed a level higher than what can be carried away by molecular diffusion from the APD enclosure to the manifold. This level will need to be determined and it is dependant on the conductance of the tube connecting the APD enclosure to the manifold tube.

Mass transport is analogous to heat energy transport, so we can map over to temperature and solve a thermal model of the APD enclosure and through the connecting tube.

$WaterConcentration = Temperature$ $Mass = Energy$ $MassFlow = HeatFlow$

$\frac{gr}{m^3} = K$ $gr = J$ $\frac{gr}{sec} = \frac{J}{sec} = W$

mass of water into APD enclosure and connecting tube

$$Water_{Permeation\_APDseal} = 2.016 \times 10^5 \cdot \frac{\mu g}{day}$$

$$Water_{Permeation\_tube} := mass_{intoHosePerLength} \cdot Length_{offshoot} = 5.69 \cdot \frac{\mu g}{hr}$$

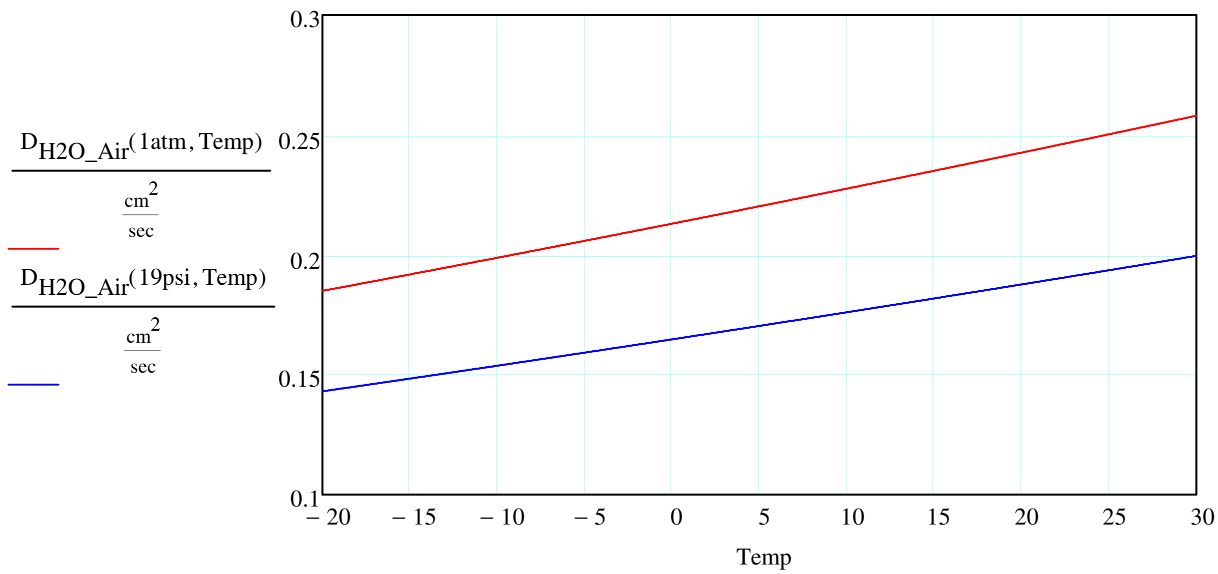
$Length_{offshoot} = 2 \cdot in$

$ID_{tube} := 0.125in$

$A_{tube} := \frac{\pi}{4} \cdot ID_{tube}^2$

Mass diffusion coefficient of Water Vapor in air WRT temperature and pressure

$$D_{H2O\_Air}(Press, Temp) := interp\left(regress\left(Diff_{Data}^{\langle 1\rangle}, Diff_{Data}^{\langle 2\rangle}, 4\right), Diff_{Data}^{\langle 1\rangle}, Diff_{Data}^{\langle 2\rangle}, Temp\right)\cdot\frac{cm^2}{sec}\cdot\frac{1atm}{Press}$$



Solve the mass transport equation (Ficks Law)

$$J = D\cdot\left(\frac{d}{dx}C\right)$$

$$mass_{flux} = Diffusion_{Coefficient}\cdot\frac{\Delta WaterConcentration}{path_{Length}}$$

$$\frac{mass_{generation}}{path_{area}} = Diffusion_{Coefficient}\cdot\frac{\Delta WaterConcentration}{path_{Length}} \text{ solve}, \Delta WaterConcentration \rightarrow \frac{mass_{generation}\cdot path_{Length}}{Diffusion_{Coefficient}\cdot path_{area}}$$

$$mass_{generation} := Water_{PermeationPerAPD} + \frac{Water_{Permeation\_tube}}{2} = 3.574\cdot\frac{\mu g}{hr}$$

$$path_{Length} := 2in$$

$$path_{area} := \frac{\pi}{4}\cdot(0.125in)^2$$

$$\Delta WaterConcentration\left(Diffusion_{Coefficient}\right) := \frac{mass_{generation}\cdot path_{Length}}{Diffusion_{Coefficient}\cdot path_{area}}$$

$$\Delta C_{APD\_Man}(Press) := \frac{mass_{generation} \cdot path_{Length}}{D_{H2O\_Air}(Press, 20) \cdot path_{area}}$$

$$\Delta C_{APD\_Man}\left(P_{NOvA} + 5psi\right) = 0.339 \cdot \frac{gr}{m^3}$$

Equivalent thermal properties of Air for mass transport

$$Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 1.184 \frac{kg}{m^3}$$

$$c_{pDmass} := \frac{1}{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)} = 8.444 \times 10^{-4} \cdot \frac{gr}{gr \cdot \frac{gr}{m^3}}$$

$$c_{pDheat} := c_{pDmass} \cdot \left(\frac{\frac{J}{kg \cdot K}}{\frac{gr}{kg \cdot \frac{gr}{m^3}}}\right) = 0.844 \cdot \frac{J}{kg \cdot K}$$

$$D_{H2O} := D_{H2O\_Air}\left(P_{NOvA} + 5psi, 20\right) = 0.188 \cdot \frac{cm^2}{sec}$$

$$k_{heat} := D_{H2O} \cdot c_{pDheat} \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 1.876 \times 10^{-5} \cdot \frac{W}{m \cdot K}$$

$$k_{mass} := D_{H2O} \cdot c_{pDmass} \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 1.876 \times 10^{-5} \cdot \frac{\frac{gr}{sec}}{m \cdot \frac{gr}{m^3}}$$

$$k_{mass} = 1.876 \times 10^{-5} \frac{m^2}{s}$$

$$Energy_{Permeation} := \left(Water_{PermeationPerAPD} + \frac{Water_{Permeation\_tube}}{2}\right) \cdot \left(\frac{W}{\frac{gr}{sec}}\right) = 0.993 \cdot nW$$

$$Max_{APDTemp} := Water_{\rho\_T}\left(Dewpoint_{Design}\right) \cdot \left(\frac{K}{\frac{gr}{m^3}}\right) = 0.552 K$$

$$ManifoldTemp := Water_{\rho\_T}(-40) \cdot \left(\frac{K}{\frac{gr}{m^3}}\right) = 0.121 K$$

$$\Delta T := Max_{APDTemp} - ManifoldTemp$$

$$AreaOverLength := \frac{Energy_{Permeation}}{\left(k_{heat} \cdot \Delta T\right)} = 1.227 \times 10^{-4} \cdot m$$

Defining equations

$$Q = k \cdot \Delta T \cdot \frac{A}{L}$$

$$Energy_{Permeation} = k_{diff} \cdot \Delta T \cdot AreaOverLength$$

$$Water_{Permeation} = k_{massTransfer} \cdot \Delta C \cdot AoverL_{mass}$$

$$Length_{tube} := \frac{A_{tube}}{AreaOverLength} = 2.54 \cdot in$$

Solving mass transport equation

$$AoverL_{mass} := \frac{Water_{PermeationPerAPD} + \frac{Water_{Permeation\_tube}}{2}}{k_{mass}\cdot\left(Water_{\rho\_T}\left(Dewpoint_{Design}\right) - Water_{\rho\_T}(-40)\right)} = 1.227\times 10^{-4}\,m$$

$$Length_{tube} := \frac{A_{tube}}{AoverL_{mass}} = 2.54\cdot in$$

At end of line we will have a higher amount of water vapor in tube, but a higher diffusion rate due to the lower pressure. We will perform the same calculation for this section of tube.

$$D_{H2O} := D_{H2O\_Air}\left(P_{NOvA} + 1psi, 20\right) = 0.238\cdot\frac{cm^2}{sec}$$

$$k_{heat} := D_{H2O}\cdot c_{pDheat}\cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 2.377\times 10^{-5}\cdot\frac{W}{m\cdot K}$$

$$k_{mass} := D_{H2O} = 2.377\times 10^{-5}\cdot\frac{\frac{gr}{sec}}{m\cdot\frac{gr}{m^3}}$$

$$k_{mass} = 2.377\times 10^{-5}\,\frac{m^2}{s}$$

$$Energy_{Permeation} := \left(Water_{PermeationPerAPD} + \frac{Water_{Permeation\_tube}}{2}\right)\cdot\left(\frac{W}{\frac{gr}{sec}}\right) = 0.993\cdot nW$$

$$Max_{APDTemp} := Water_{\rho\_T}\left(Dewpoint_{Design}\right)\cdot\left(\frac{K}{\frac{gr}{m^3}}\right) = 0.552\,K$$

Defining equations

$$Q = k\cdot\Delta T\cdot\frac{A}{L}$$

$$ManifoldTemp := Water_{\rho\_T}\left(Dewpoint_{Design}\right)\cdot 50\%\cdot\left(\frac{K}{\frac{gr}{m^3}}\right) = 0.276\,K$$

$$Energy_{Permeation} = k_{diff}\cdot\Delta T\cdot AreaOverLength$$

$$Water_{Permeation} = k_{massTransfer}\cdot\Delta C\cdot AoverL_{mass}$$

$$\Delta T := Max_{APDTemp} - ManifoldTemp$$

$$AreaOverLength := \frac{Energy_{Permeation}}{\left(k_{heat}\cdot\Delta T\right)} = 1.514\times 10^{-4}\cdot m$$

$$Length_{tube} := \frac{A_{tube}}{AreaOverLength} = 2.059\cdot in$$

Solving mass transport equation

$$AoverL_{mass} := \frac{Water_{Permeation\_APDseal} + \frac{Water_{Permeation\_tube}}{2}}{k_{mass} \cdot \left(Water_{\rho\_T}\left(Dewpoint_{Design}\right) - Water_{\rho\_T}\left(Dewpoint_{Design}\right) \cdot 25\%\right)} = 0.237\,m$$

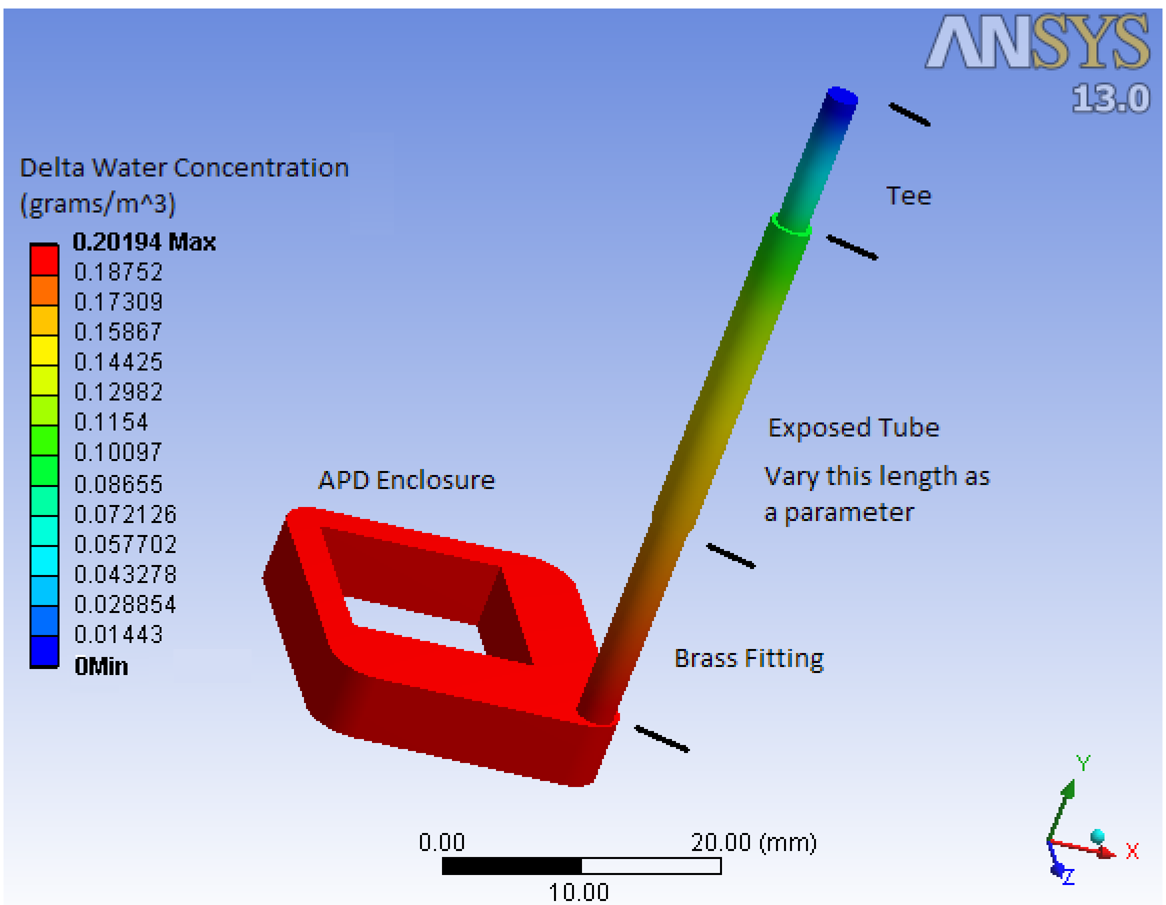
$$Length_{tube} := \frac{A_{tube}}{AoverL_{mass}} = 0.001 \cdot in$$

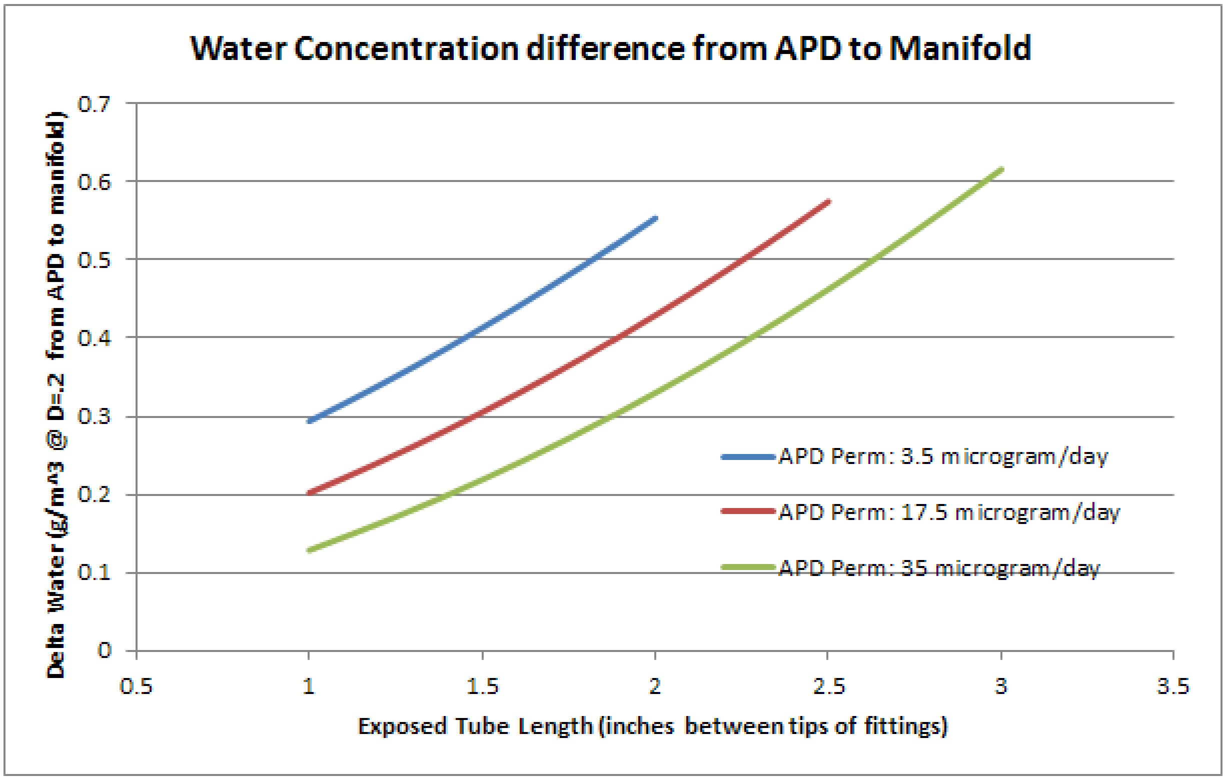
Find the difference in water concentration from the manifold the APD enclosure if we use a 1/8" hose, vary the length of the Hose, Use FEA Model to take into account 3D physics. Make model parametric to study design space

$ID_{tube} := 0.125in$ $\qquad A_{tube} := \frac{\pi}{4} \cdot ID_{tube}^{\ 2}$

Boundary Conditions:

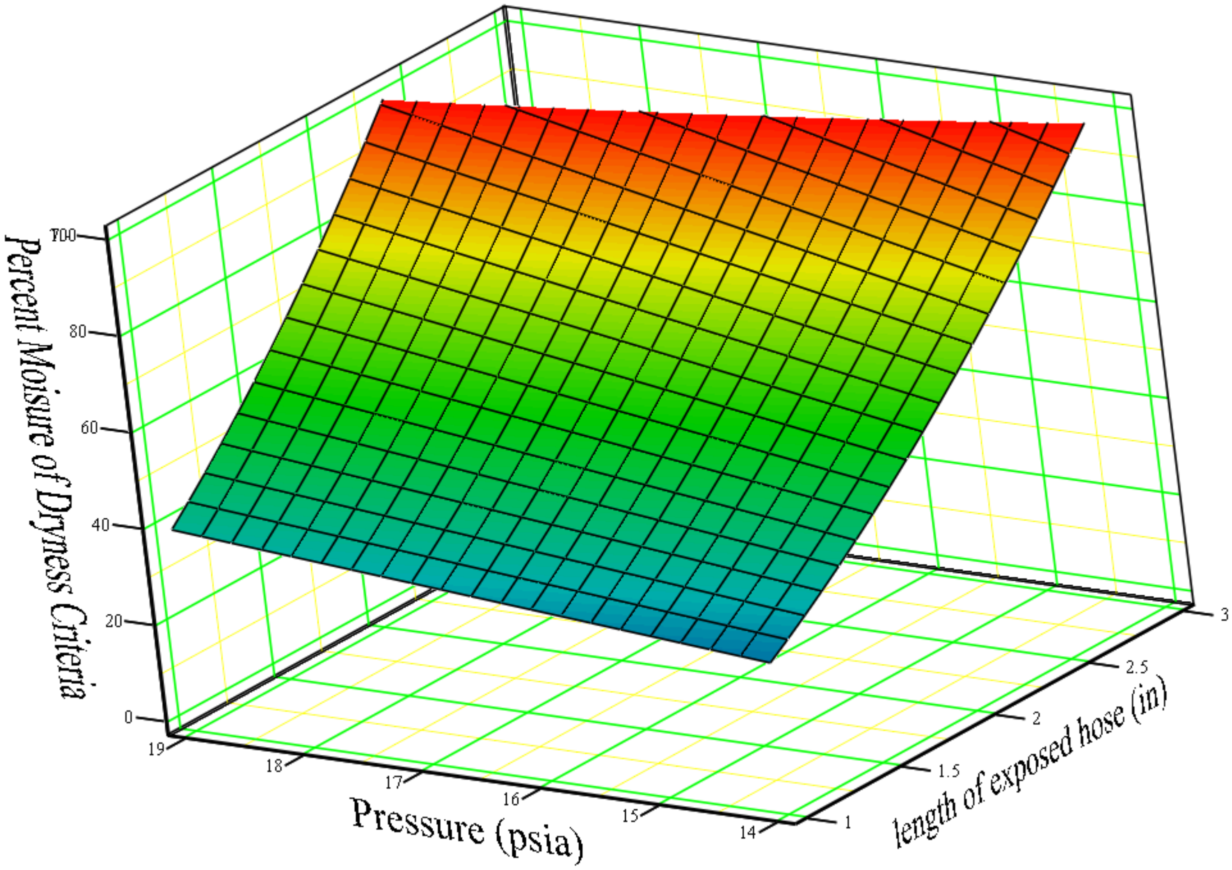
Permeate water into APD Enclosure,
Permeate Water through "Exposed tube"
Hold Manifold water concentration constant





$$l_{path} := \frac{path_{Length}}{in}$$

$$\Delta C_{H2O}(l_{path}, Press) := \left(0.042219189 \cdot l_{path}^{2} + 0.100675545 \cdot l_{path} + 0.059045436\right) \cdot \frac{gr}{m^{3}} \cdot \left(\frac{0.2 \frac{cm^{2}}{sec}}{D_{H2O\_Air}(Press, 20)}\right)$$



PercentOfDrynessCriteria

SystemFlow = 1.296·SCFM

SystemFlowSpec := 2SCFM

$Air_{pressure}$ = 18·psi

Pipe or Tube Manifold Sizing (Pressure Drop Calculations)

$d_{manifold} := 0.125in$ $A_{manifold} := \frac{\pi}{4} \cdot d_{manifold}^{2}$ $\mu_{air} := 0.000018453Pa \cdot sec$

$Length_{Detector} := 5.25in \cdot 32 \cdot 15$

$$manifold_{flow} := \frac{SystemFlowSpec \cdot \left(\frac{1atm}{Air_{pressure}}\right)}{num_{row}} = 0.0680368 \cdot \frac{ft^{3}}{min}$$

$$V_{flowMan} := \frac{manifold_{flow}}{A_{manifold}} = 4.056 \frac{m}{s}$$

$$Re := \frac{Air_{\rho\_P}\left(\frac{Air_{pressure}}{psi}\right) \cdot V_{flowMan} \cdot d_{manifold}}{\mu_{air}} = 1012.305$$

Laminar flow

$$f := \frac{64}{Re} = 0.063$$

$$\Delta P := f \cdot \left(\frac{Length_{Detector}}{d_{manifold}} \cdot \frac{V_{flowMan}^{2}}{2} \cdot Air_{\rho\_P}\left(\frac{Air_{pressure}}{psi}\right)\right) = 2.205 \cdot psi$$

System could consist of 1/8" ID tube manifolds running the entire length of the detector with any size tubes connecting the manifolds to the APD enclosures.

Mathematically equivalent we can calculate according to standard conditions and multiply by a correction factor for pressure: (P1/P2) this means it only depends on the volume flow rate of the gas, not the mass flow rate of the pressurized gas. so using constant mass flow rate we just divide by the pressure ratio.

$$manifold_{flow} := \frac{SystemFlowSpec}{num_{row}} = 0.083 \cdot SCFM$$

$$V_{flowMan} := \frac{manifold_{flow}}{A_{manifold}} = 4.967 \frac{m}{s}$$

$$Re := \frac{Air_{\rho\_P}\left(\frac{1atm}{psi}\right) \cdot V_{flowMan} \cdot d_{manifold}}{\mu_{air}} = 1012.23$$

$$f := \frac{64}{Re} = 0.063$$

$$\Delta P := f \cdot \left(\frac{Length_{Detector}}{d_{manifold}} \cdot \frac{V_{flowMan}^{2}}{2} \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right) = 2.701 \cdot psi$$

$$manifold_{flow} := \frac{SystemFlowSpec}{num_{row}} = 0.083 \cdot SCFM \qquad V_{flowMan} := \frac{manifold_{flow}}{A_{manifold}} = 4.967 \frac{m}{s}$$

$$Re := \frac{Air_{\rho\_P}\left(\frac{1atm}{psi}\right) \cdot V_{flowMan} \cdot d_{manifold}}{\mu_{air}} = 1012.23 \qquad f := \frac{64}{Re} = 0.063$$

$$\Delta P_{tube} := f \cdot \left(\frac{1}{d_{manifold}} \cdot \frac{V_{flowMan}^{2}}{2} \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right) \cdot \left(\frac{1atm}{Air_{pressure}}\right) = 0.011 \cdot \frac{psi}{ft}$$

$$\Delta P_{tubes} := Length_{Detector} \cdot \Delta P_{tube} = 2.205 \cdot psi$$

$$d_{tee} := 0.092in \qquad A_{tee} := \frac{\pi}{4} \cdot d_{tee}^{2} \qquad L_{tee} := 0.994in \qquad num_{tees} := 15 \cdot 32 = 480$$

$$manifold_{flow} := \frac{SystemFlowSpec}{num_{row}} = 0.083 \cdot SCFM \qquad V_{flowTee} := \frac{manifold_{flow}}{A_{tee}} = 9.17 \frac{m}{s}$$

$$Re := \frac{Air_{\rho\_P}\left(\frac{1atm}{psi}\right) \cdot V_{flowTee} \cdot d_{tee}}{\mu_{air}} = 1375.312 \qquad f := \frac{64}{Re} = 0.047$$

$$\Delta P_{tee} := f \cdot \left(\frac{L_{tee}}{d_{tee}} \cdot \frac{V_{flowTee}^{2}}{2} \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right) = 0.004 \cdot \frac{psi}{tee}$$

$$\Delta P_{tees} := \Delta P_{tee} \cdot num_{tees} = 1.743 \cdot psi$$

Sudden contractions/Enlargements

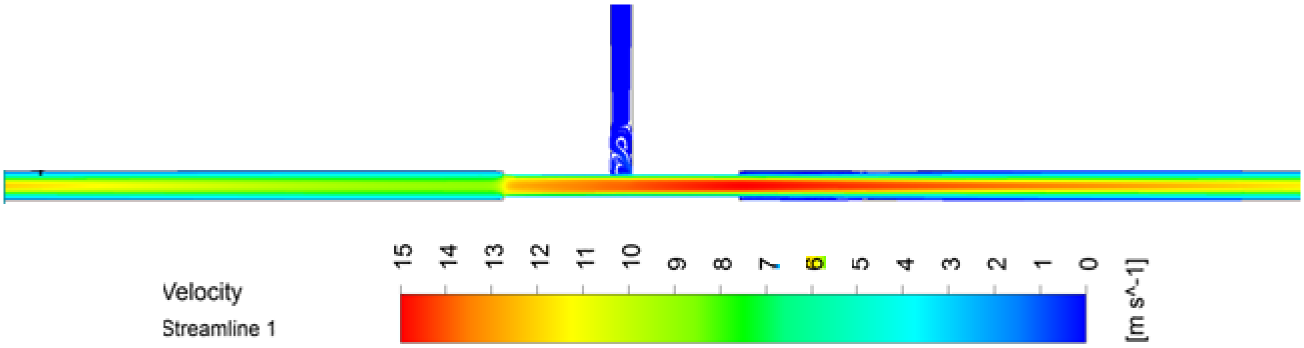
$$\beta := \frac{d_{tee}}{d_{manifold}} = 0.736 \qquad K_C := 0.5\left(1 - \beta^2\right)^2 = 0.105 \qquad K_E := \left(1 - \beta^2\right)^2 = 0.21$$

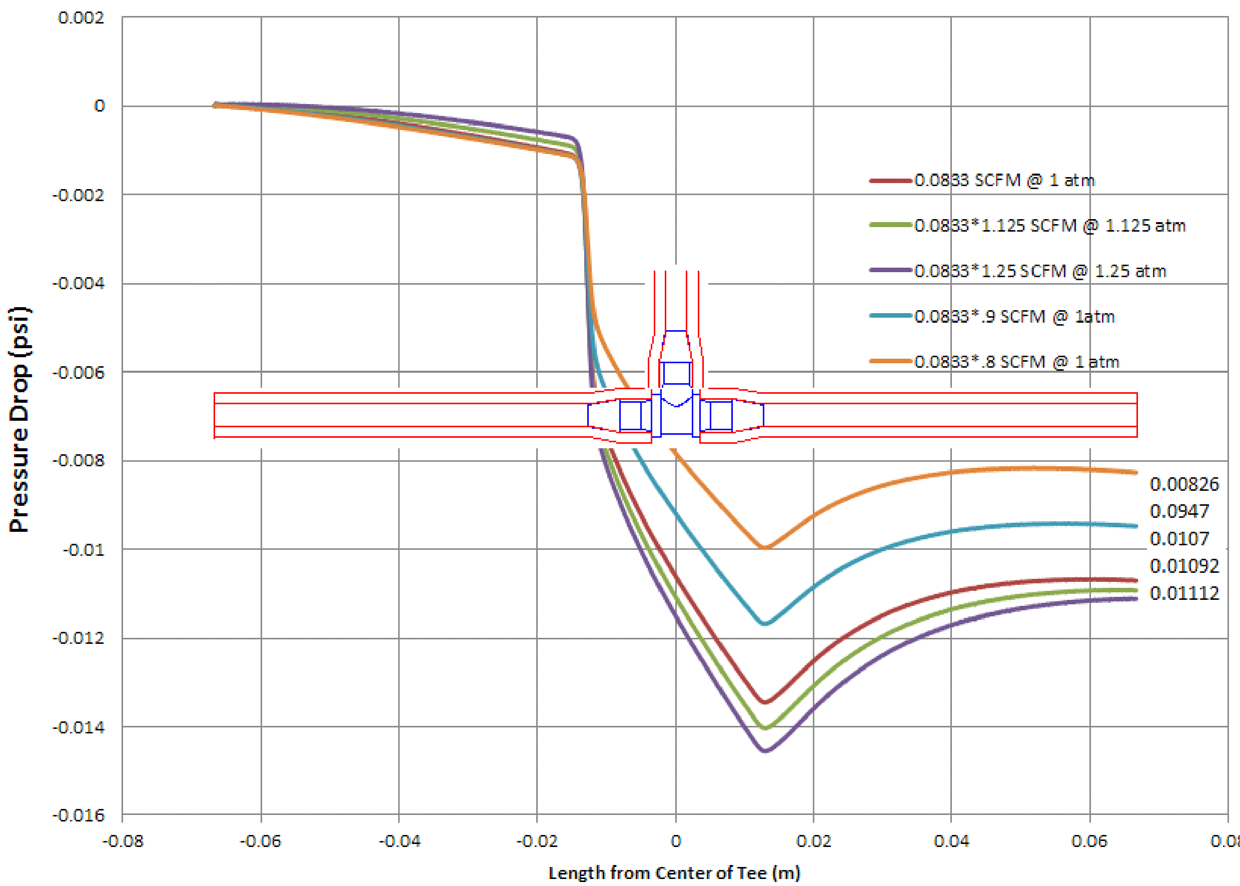
$$\Delta P_{Cont\_Exp} := 480 \cdot \left(K_C + K_E\right) \cdot \left(\frac{V_{flowTee}^{2}}{2} \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right) = 1.092 \cdot psi$$

Total Pressure Drop

$$DP_{total} := \Delta P_{tees} + \Delta P_{tubes} + \Delta P_{Cont\_Exp} = 5.041 \cdot psi$$

Since all these calculations are for fully developed flow, they may not be accurate as our flow travels through hundreds on contractions/expansions and never becomes fully developed. For this reason we will run a parametric CFD model of an equivalent section of the tube/tees which uses periodic boundary conditions simulating an infinite number of these in a row.





Curve fit to CFD Data:

$$\Delta P_{CFD}(Press, mass_{flow}) := \left[0.001867709 \cdot \left(\frac{mass_{flow}}{46.578\ \frac{mg}{sec}}\right)^2 + 0.008834883 \cdot \frac{mass_{flow}}{46.578\ \frac{mg}{sec}}\right] \cdot psi \cdot \frac{atm}{Press}$$

for later program

Detailed System Analysis

We will write a program to calculate the mass flow rates, pressures, water concentrations, ΔC.APD to manifold, and dew points at each node along a route. We will make several parameters which we can change at will and recalculate to study the design space and affects of slight variable changes

Water content of air coming out of the drier:

$Dewpoint_{atDrier} := -40$

$Water_{contentDrier\rho} := Water_{\rho\_T}(Dewpoint_{atDrier}) = 0.121 \cdot \frac{\mu g}{mL}$

$Water_{\rho\_T}(Dewpoint_{Design}) = 0.552 \cdot \frac{\mu g}{mL}$

$Water_{contentDrierP} := Water_{P\_T}(Dewpoint_{atDrier}) = 13.006 \cdot Pa$

$Water_{P\_T}(Dewpoint_{Design}) = 63.18\, Pa$

Pressure From The Drier

$P_{Drier} := 4psi + P_{NOvA}$

$SystemFlowSpec := 1.75SCFM$

Permeation rate of hose, this will be tested.

$Perm_{hose} := 0.1000 \frac{gm \cdot mm}{m^2 \cdot day \cdot kPa}$

$ManifoldFlowSpec := \frac{SystemFlowSpec}{num_{rows}} = 0.073 \cdot SCFM$

$ManifoldFlowSpec = 4.375\, SCFH$

$manifold_{Mflow} := ManifoldFlowSpec \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 40.756 \cdot \frac{mg}{sec}$

Water Permeation through tubes and APDs

$APD_{pitch} := 5.25in$

$Length_{offshoot} := 2in$

$tube_{length\_node} := APD_{pitch} + Length_{offshoot} = 7.25 \cdot in$

$A_{hoseNode} := \pi \cdot \frac{(ID_{hose} + OD_{hose})}{2} \cdot tube_{length\_node}$

$t_{hose} := \frac{OD_{hose} - ID_{hose}}{2}$

Partial Pressure of water at 25C and 90% relative humidity

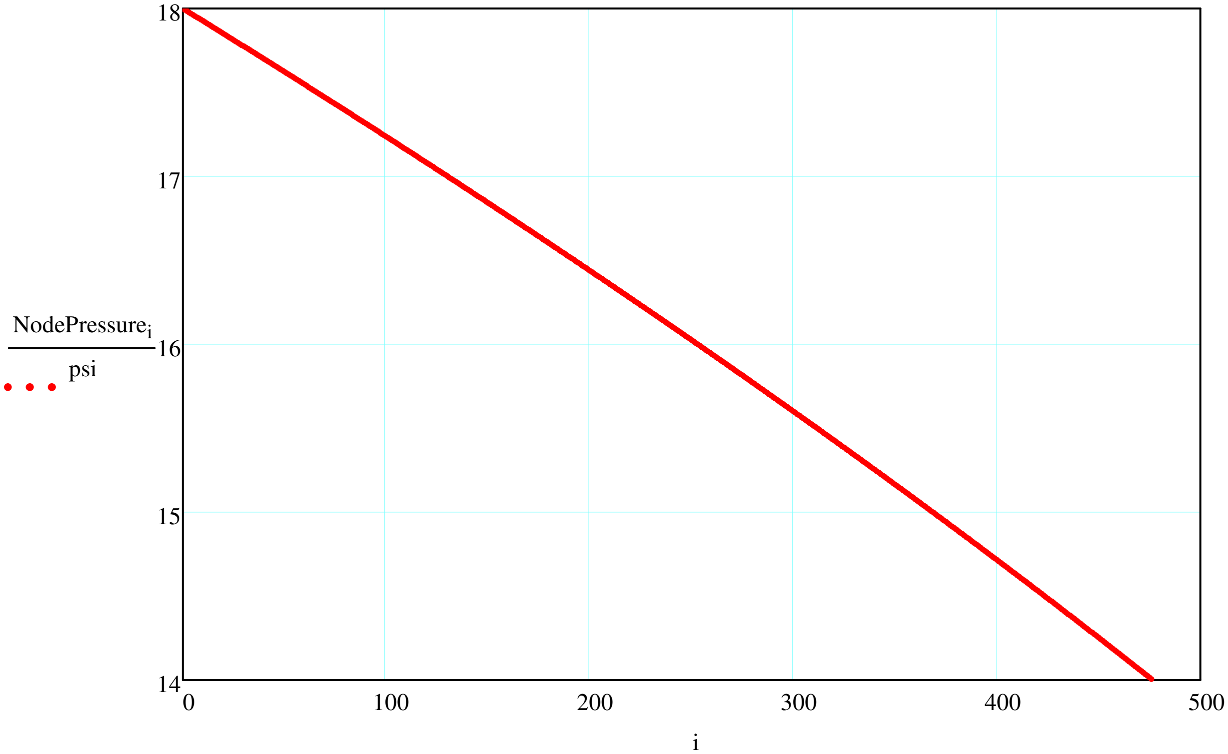
$$Ambient_{waterP} := Water_{P\_T}(25)(90\%) = 2852.112\,Pa$$

$$Ambient_{water\rho} := Water_{\rho\_T}(25)(90\%) = 20.761 \cdot \frac{\mu g}{mL}$$

$$mass_{intoHosePM} = \frac{Perm_{hose} \cdot Area_{hose} \cdot (\Delta C)}{t_{hose}}$$

$$num_{APDinROW} := 15 \cdot 32 = 480$$

$$
NodePressure := \left|
\begin{array}{l}
NodePressure_0 \leftarrow P_{Drier} \\
manifold_{massflow_0} \leftarrow manifold_{Mflow} \\
\text{for } i \in 1 .. num_{APDinROW} \\
\quad \left|
\begin{array}{l}
Leak_{outAPD_i} \leftarrow APD_{flowLeak}\left(NodePressure_{i-1}\right) \\
DP_{node_i} \leftarrow \Delta P_{CFD}\left(NodePressure_{i-1}, manifold_{massflow_{i-1}}\right) \\
manifold_{massflow_i} \leftarrow manifold_{massflow_{i-1}} - Leak_{outAPD_i} \\
NodePressure_i \leftarrow NodePressure_{i-1} - DP_{node_i}
\end{array}
\right. \\
\text{return } NodePressure
\end{array}
\right.
$$



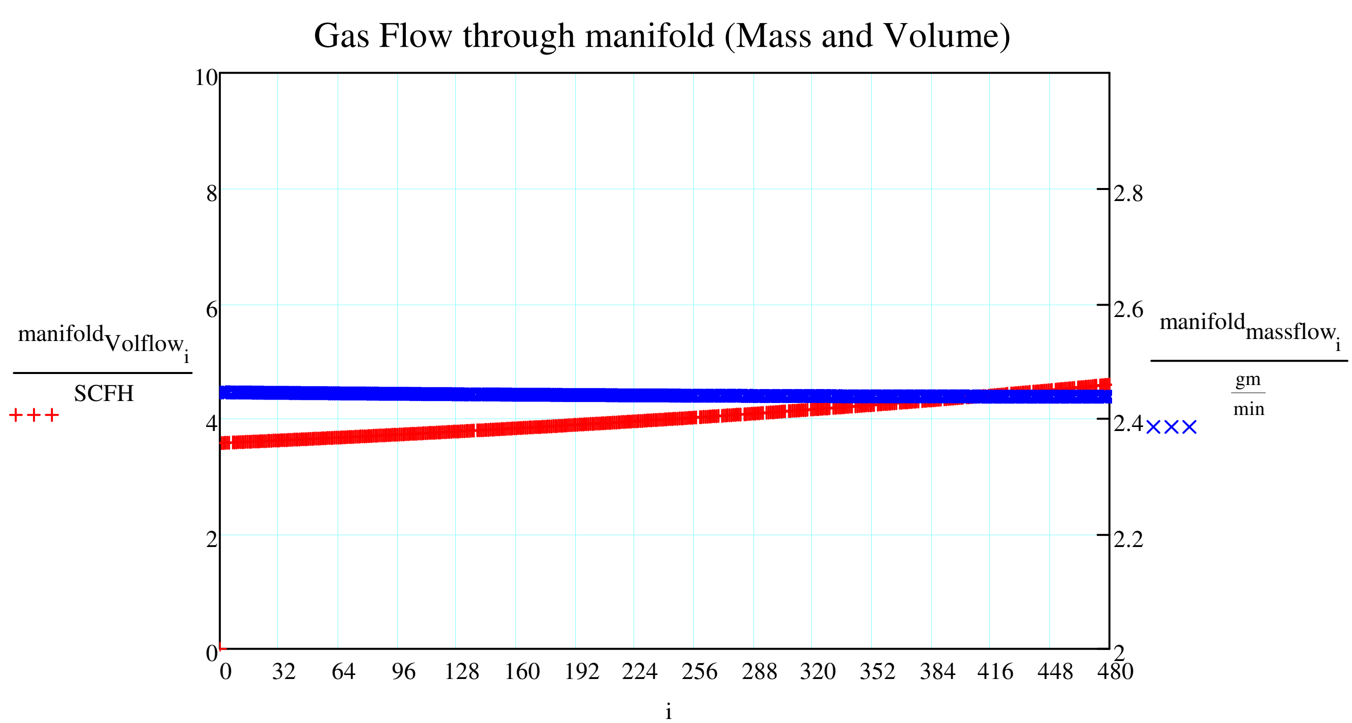
$$NodePressure_{480} = 13.97\,psi$$

$$\mathrm{Water}_{content} := \left| \begin{array}{l} \mathrm{Water}_{content_0} \leftarrow \mathrm{Water}_{contentDrier\rho} \\ \text{for } i \in 1 .. \mathrm{num}_{APDinROW} \\ \quad \left| \begin{array}{l} \mathrm{manifold}_{Volflow_i} \leftarrow \dfrac{\mathrm{manifold}_{massflow_i}}{\mathrm{Air}_{\rho\_P}\left(\dfrac{\mathrm{NodePressure}_i}{\mathrm{psi}}\right)} \\ \mathrm{WaterPermeating}_i \leftarrow \dfrac{\mathrm{Perm}_{hose\rho} \cdot A_{hoseNode} \cdot \left(\mathrm{Ambient}_{water\rho} - \mathrm{Water}_{content_{i-1}}\right)}{t_{hose}} + \mathrm{Water}_{PermeationPerAPD} \\ \mathrm{Water}_{content_i} \leftarrow \mathrm{Water}_{content_{i-1}} + \dfrac{\mathrm{WaterPermeating}_i}{\mathrm{manifold}_{Volflow_i}} \end{array} \right. \\ \text{return } \mathrm{Water}_{content} \end{array} \right.$$

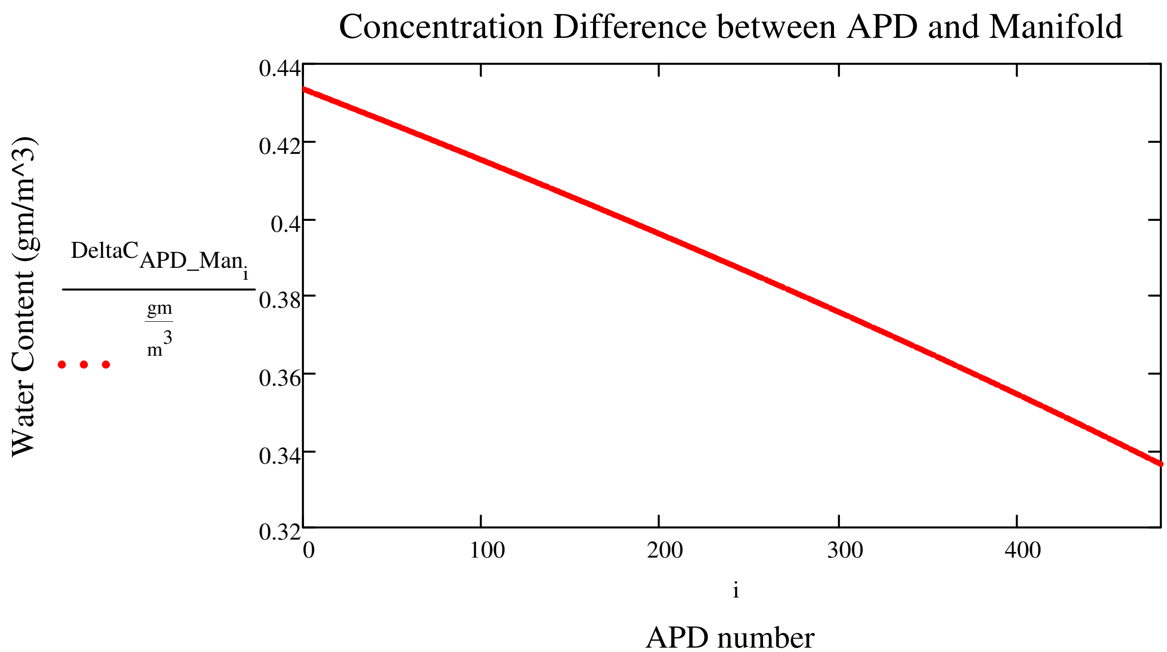
$$\mathrm{WaterPermeating} := \left| \begin{array}{l} \mathrm{Water}_{content_0} \leftarrow \mathrm{Water}_{contentDrier\rho} \\ \text{for } i \in 1 .. \mathrm{num}_{APDinROW} \\ \quad \left| \begin{array}{l} \mathrm{manifold}_{Volflow_i} \leftarrow \dfrac{\mathrm{manifold}_{massflow_i}}{\mathrm{Air}_{\rho\_P}\left(\dfrac{\mathrm{NodePressure}_i}{\mathrm{psi}}\right)} \\ \mathrm{WaterPermeating}_i \leftarrow \dfrac{\mathrm{Perm}_{hose\rho} \cdot A_{hoseNode} \cdot \left(\mathrm{Ambient}_{water\rho} - \mathrm{Water}_{content_{i-1}}\right)}{t_{hose}} + \mathrm{Water}_{PermeationPerAPD} \\ \mathrm{Water}_{content_i} \leftarrow \mathrm{Water}_{content_{i-1}} + \dfrac{\mathrm{WaterPermeating}_i}{\mathrm{manifold}_{Volflow_i}} \end{array} \right. \\ \text{return } \mathrm{WaterPermeating} \end{array} \right.$$

$$
\begin{aligned}
manifold_{Volflow} := \; & Water_{content_0} \leftarrow Water_{contentDrier\rho} \\
& \text{for } i \in 1 .. num_{APDinROW} \\
& \quad manifold_{Volflow_i} \leftarrow \frac{manifold_{massflow_i}}{Air_{\rho\_P}\left(\frac{NodePressure_i}{psi}\right)} \\
& \quad WaterPermeating_i \leftarrow \frac{Perm_{hose\rho} \cdot A_{hoseNode} \cdot \left(Ambient_{water\rho} - Water_{content_{i-1}}\right)}{t_{hose}} + Water_{PermeationPerAPD} \\
& \quad Water_{content_i} \leftarrow Water_{content_{i-1}} + \frac{WaterPermeating_i}{manifold_{Volflow_i}} \\
& \text{return } manifold_{Volflow}
\end{aligned}
$$

$$
\begin{aligned}
DewPoint_{manifold} := \; & \text{for } i \in 0 .. num_{APDinROW} \\
& \quad DewPoint_{manifold_i} \leftarrow DewPoint_{T\_\rho}\left(\frac{Water_{content_i}}{\frac{kg}{m^3}}\right) \\
& \text{return } DewPoint_{manifold}
\end{aligned}
$$

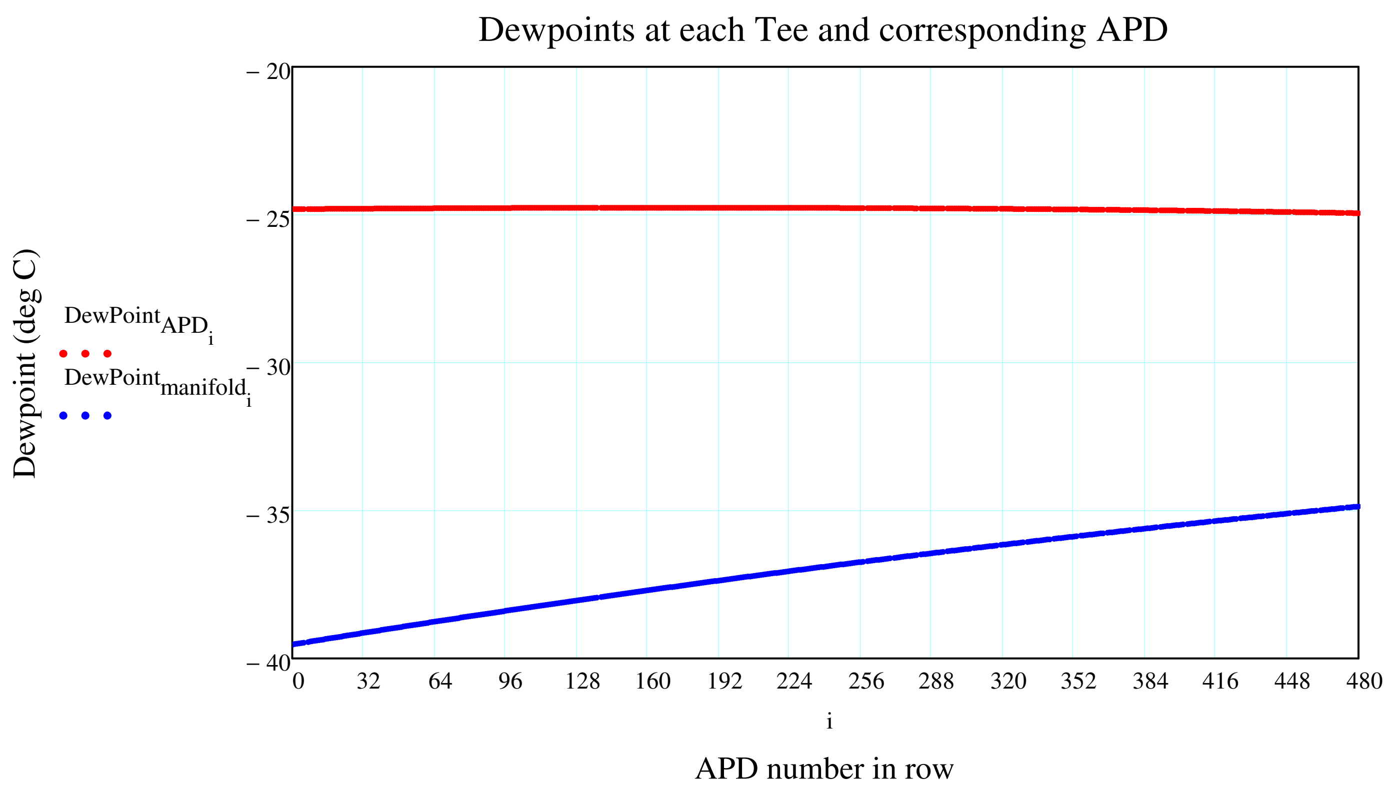


$$\mathrm{DeltaC}_{\mathrm{APD\_Man}} := \left|\begin{array}{l} \text{for } i \in 0..\mathrm{num}_{\mathrm{APDinROW}} \\ \quad \mathrm{DeltaC}_{\mathrm{APD\_Man}_i} \leftarrow \Delta C_{\mathrm{H2O}}\left(l_{\mathrm{path}}, \mathrm{NodePressure}_i\right) \\ \text{return } \mathrm{DeltaC}_{\mathrm{APD\_Man}} \end{array}\right.$$

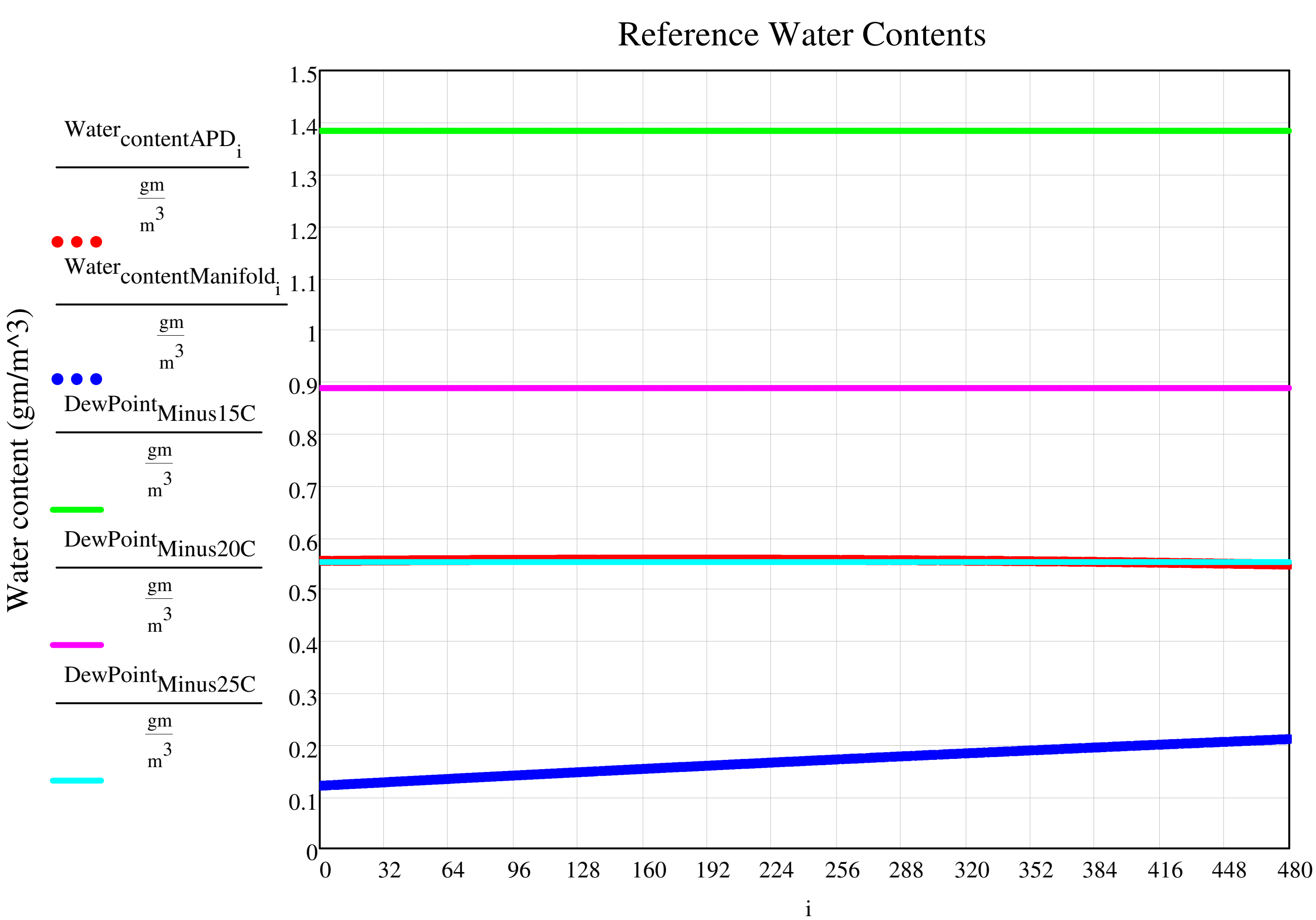


$$\mathrm{DewPoint}_{\mathrm{APD}} := \left|\begin{array}{l} \text{for } i \in 0..\mathrm{num}_{\mathrm{APDinROW}} \\ \quad \mathrm{DewPoint}_{\mathrm{APD}_i} \leftarrow \mathrm{DewPoint}_{\mathrm{T\_\rho}}\left(\dfrac{\mathrm{Water}_{\mathrm{content}_i} + \mathrm{DeltaC}_{\mathrm{APD\_Man}_i}}{\dfrac{\mathrm{kg}}{\mathrm{m}^3}}\right) \\ \text{return } \mathrm{DewPoint}_{\mathrm{APD}} \end{array}\right.$$

$$\mathrm{Water}_{\mathrm{contentAPD}} := \left|\begin{array}{l} \text{for } i \in 0..\mathrm{num}_{\mathrm{APDinROW}} \\ \quad \mathrm{Water}_{\mathrm{contentAPD}_i} \leftarrow \left(\mathrm{Water}_{\mathrm{content}_i} + \mathrm{DeltaC}_{\mathrm{APD\_Man}_i}\right) \\ \text{return } \mathrm{Water}_{\mathrm{contentAPD}} \end{array}\right.$$



Dewpoints at each Tee and corresponding APD
Dewpoint (deg C)
DewPoint APD i
DewPoint manifold i
− 20
− 25
− 30
− 35
− 40
0 32 64 96 128 160 192 224 256 288 320 352 384 416 448 480
i
APD number in row



Reference Water Contents
Water content (gm/m^3)
Water contentAPD i / gm/m3
Water contentManifold i / gm/m3
DewPoint Minus15C / gm/m3
DewPoint Minus20C / gm/m3
DewPoint Minus25C / gm/m3
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 32 64 96 128 160 192 224 256 288 320 352 384 416 448 480
i