Inner Detector Cooling Review

Pixels
Evaporative Cooling Analysis
May 1999

W.O. Miller
HYTEC

Evaporative Cooling

Analysis of Vapor Return

- **Basic Approach**
  - **Low pressure C_4F_{10} evaporative cooling of detector modules**
    - **concept demonstrated with extensive prototype testing**
    - **employs wet mixture of vapor achieved through throttling fluid at nominally 2 bar at entrance to carbon-carbon thermostructures**
    - **~500 mbar wet mixture evaporates in thermostructure, exiting at quality on the order of 0.88(?)**
    - **low pressure in the thermostructures, as opposed to very high pressures:**
      - **limit distortion**
      - **minimize material**
      - **reduce risk**
- ***Questions to be addressed in this discussion***
  - ***What impact does a low pressure system choice have on the vapor return line size***
  - ***Would we be wise to seriously consider a condenser?***

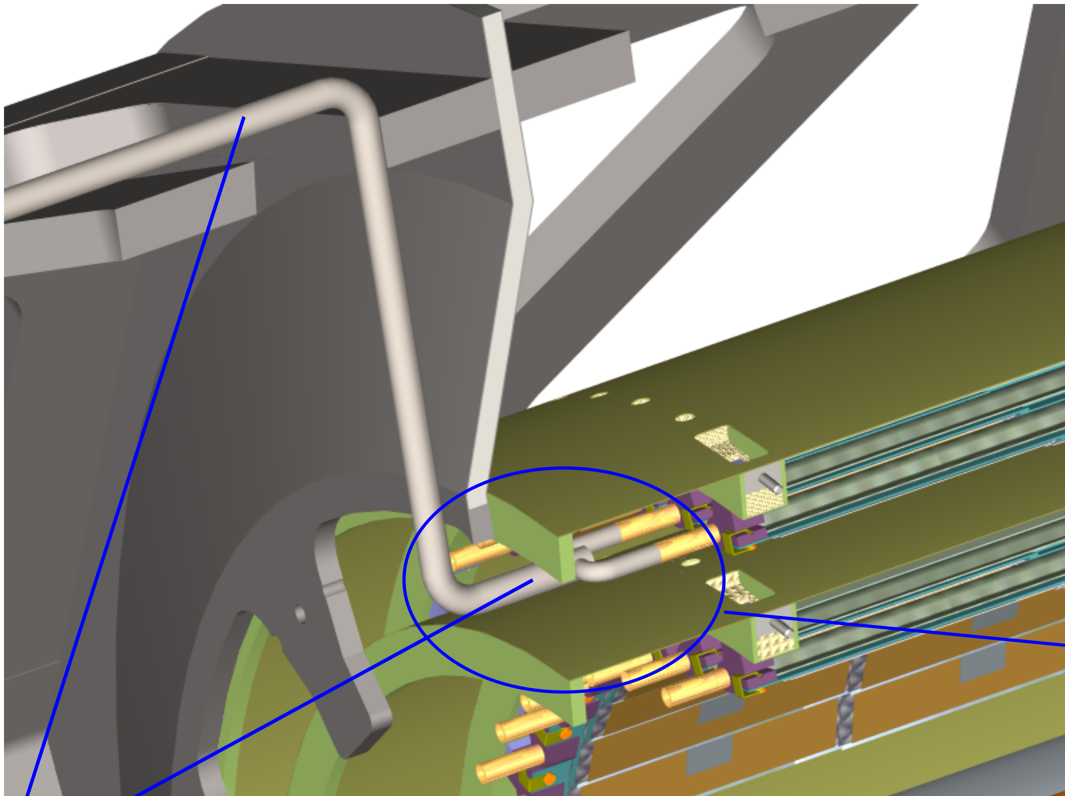
C_4F_{10} Cooling Analysis

Analysis Scope

- **Fluid calculations for vapor return-*first cut to verify low pressure concept***
  - **establish minimum line size consistent with objective of providing 250 mbar at a compressor or a condenser inlet, depending upon concept**
  - **Consider potential flow states *and their effect on line losses***
    - **single phase vapor-**
      - **isothermal versus adiabatic wall condition**
      - **minimizes system complexity and pressure gradients**
      - **potential incompressible flow solution for Mach number<0.3**
    - **two phase flow-**
      - **evaluate effect of quality (0.5 to >0.9) on pressure gradients in vapor return line**
- **System concept-*arrive at technical approach for low pressure system***
  - **Condenser versus compressor concept**
  - **Thermodynamics of system operation and conservation of fluid inventory**

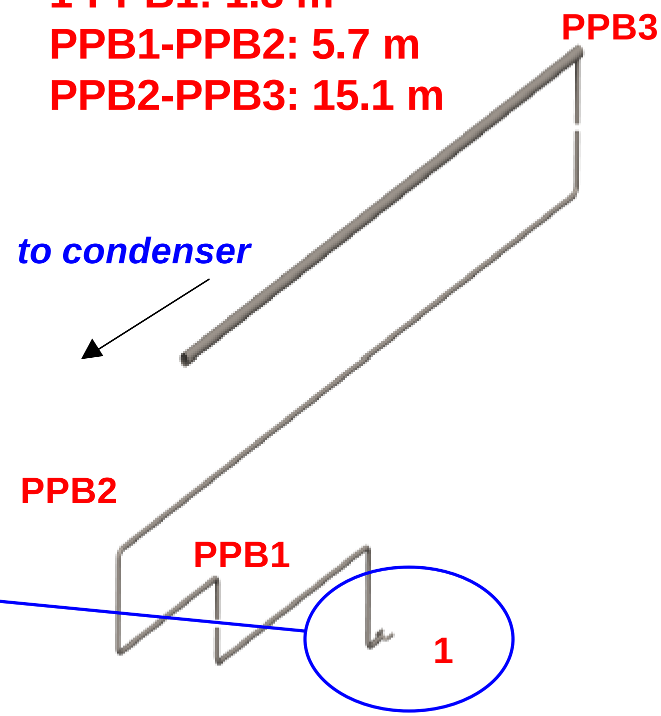
Return Vapor Line

Stave Return Line Used As Example



Path lengths-new

1-PPB1: 1.8 m
PPB1-PPB2: 5.7 m
PPB2-PPB3: 15.1 m



Region of smallest tube size and highest velocity

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Return Vapor Line

Evaluation Process

- General approach
  - first cut at tube sizes within the detector region where space constraints impose significant limitations on size
    - started with <6 mm initial tube ID
  - iterate with staff working service layout for larger tube, as required
  - make first cut at heat gain and tube outer surface temperatures
    - will require a number of iterations
  - evaluate prospect for achieving minimum 250 mbar return pressure out to 140 meters
    - presumed location of compressor
  - Based solution on 450 mbar exit pressure from stave
    - 200 mbar allowed if 250 mbar is to be realized at compressor inlet

Case A

Single Phase- Dry Vapor Return

(6 mm diameter)

Tube Section	Tube Diameter mm	Pressure Loss mbar	Static Exit Pressure mbar	Fluid Velocity m/sec	Fluid Density kg/m^3	Remarks
@ Stave exit	3.4		450	41.9	5.1	Complete loss of dynamic head
Stave manifold Y-Branch	6 after Branch	8		16.8	5.01	Accounts for pressure loss merging into 6 mm tube
			441.7	16.8	5.01	Entrance to 1.5 m run
1.5 m	6	39.3				
	6	11.2				3 elbows
		50.5 combined	391.2	18.98	4.44	Exit after 1.5 m run
5.4	6	208.2				
		21.7				3 elbows
		229.9 combined	136.5	46.03	1.83	Exit after 5.4 m run
25	13	6.3	141.6	4.7	1.61	Exit after 25 m run, with some pressure recovery

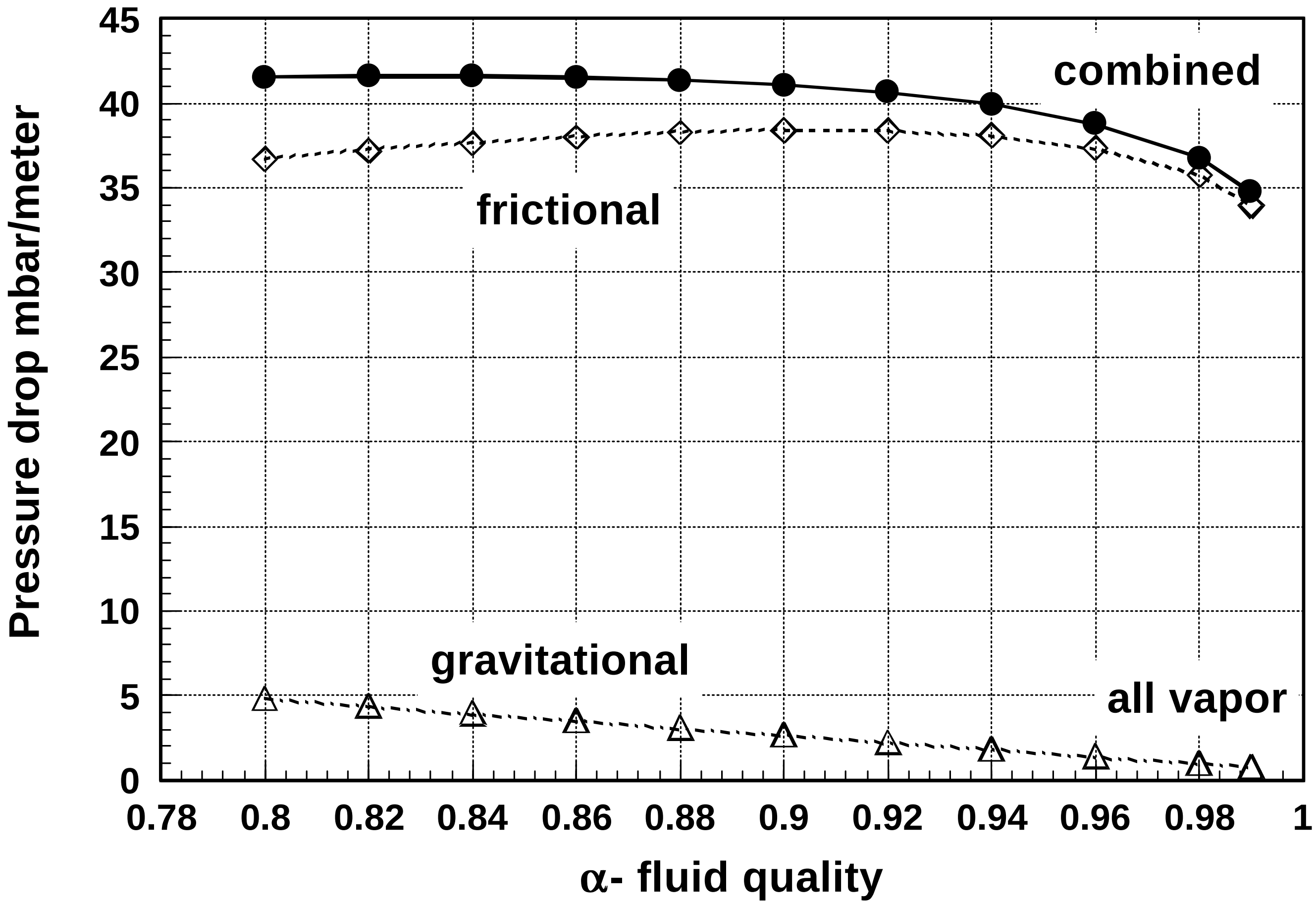
Goal of >250 mbar not satisfied at exit

(Mach~0.5, compressible flow solution req'd)

Case B

Two Phase Flow- Pressure Drop

(6 mm diameter)



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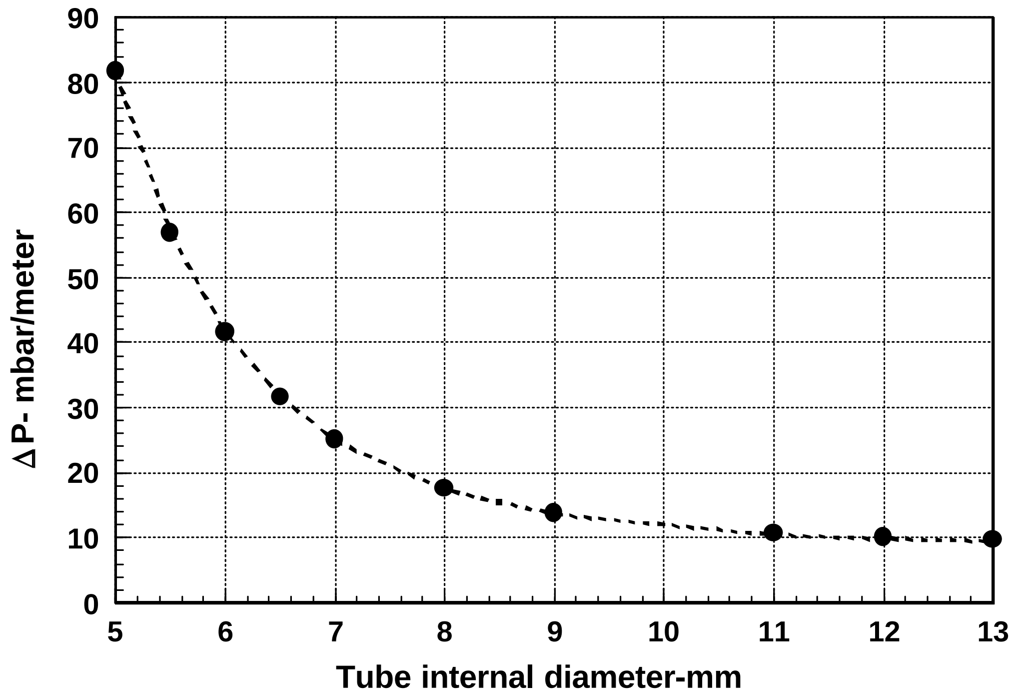
Case B

Two Phase Flow- Line Pressure Drop
(88% exit quality)

- Pressure drop contributions
  - two phase flow estimation
  - frictional +gravitational
  - based on separated flow model
- Conclusion
  - Internal tube diameter approaching 7 mm would be recommended
  - pressure drop for 1.5 tube run of 7 mm tube diameter with associated elevation change change of 1.5 meter
    - 37.5 mbar,about double to single phase fluid estimation*



*slide 10

Decision on Small Tubes

Two Phase Flow-versus Single Phase

<6 mm tube diameter not practical, >6mm desirable

- **Reference P.B. Whalley "Boiling-Condensation and Gas-Liquid Flow" for *two phase flow models***
  - **Return pressure loss estimated using separated flow model**
  - **Frictional and gravitational pressure terms, *no elbow losses included***
  - **Void fraction for fluid quality of 0.8 essentially equal to 1, nearly all vapor**
- **Single Phase Flow**
  - **Dry vapor return (x_o~1.0)**
  - **Compressible flow regime**
  - **Isothermal flow solution in inner detector region**
  - **Ignored gravitational term, since density decreased quickly**
- **Single Phase Results**
  - **26.2 mbar/meter first 1.5 meters**
  - **35 mbar/meter next 5.4 meters**
  - **local pressure decayed to point where Mach number approached 0.5**
  - **iterative solution required**
  - **Critical flow would occur at tube diameter 4.7 mm and 2.5 meters**
  - ***Conclusion tube diameter too small, recommend 7 mm initially***
- **Two Phase Results**
  - **Comparable results at quality of 0.98 (singularity occurs at α=1) 35 mbar/meter**
  - **gravitational pressure gradient becomes significant at low quality**
  - **Pressure loss on the order of 242 mbar in first 6.9 meters at tube diameter of 6 mm, without considering elbow losses**
  - ***Conclusion tube diameter too small at 6 mm***

Case A-Summary

Single Phase- Dry Vapor Return

(7 mm diameter return)

Tube Section	Tube Diameter mm	Pressure Loss mbar	Static Exit Pressure mbar	Fluid Velocity m/sec	Fluid Density kg/m^3	Remarks
@ Stave exit	3.4		450	41.9	5.1	Complete loss in dynamic head
Stave manifold Y-Branch	7 after Branch	8		16.8	5.01	Accounts for pressure loss merging into 7 mm tube
			445.5	12.24	5.05	Entrance to 1.5 m run
1.5 m	7	18.3				
	7	5.8				3 elbows
		24.1 combined	421.4	12.94	4.78	Exit after 1.5 m run
5.4	9	21.2				
		2.3				3 elbows
		23.5 combined	395.7	8.3	4.5	Exit after 5.4 m run
25	13	2.3	394.2	1.7	1.61	Exit after 25 m run

Tube size resulted in incompressible flow throughout.

Case B-Summary

Two Phase Flow Up to 5.4 meters

Tube Section	Tube Diameter mm	Pressure Loss mbar	Static Exit Pressure mbar	Vapor Velocity m/sec	Psuedo Fluid Density kg/m^3	Remarks
@ Stave exit	3.4		450	41.9	5.1	Complete loss in dynamic head
Stave manifold Y-Branch	7 after Branch	8				
			442	8.3	7.7	Entrance to 1.5 m run
1.5 m	7	37.5				
	7	11.4				3 elbows
		56.9 combined	385.1	8.3	7.7	Exit after 1.5 m run
5.4	9	74.2		5.7		
		2.3				3 elbows
		76.5 combined	308.6	8.3	4.5	Exit after 5.4 m run
25	13	2.3	306.3*	1.7	1.61	Exit after 25 m run
						*assumed to be all vapor at this point

More analysis needed--must define at what point system is all vapor
part of next step in analysis

Pressure Drop

Preliminary Conclusions-Based on Stave Model
(7 mm diameter tube)

- **Two Phase Flow-estimate**
  - ***total rough estimate of static pressure <u>306 mbar</u>***
    - ***after 31 meters, with some pressure variance around detector of the order of 8.25 mbar***
- **Single Phase Flow-estimate**
  - ***total rough estimate of static pressure <u>394 mbar</u>***
    - ***after 31 meters, with no known pressure variance around detector of the unless tube geometry is asymmetric***
- ***Two solution methods give slightly different results***
  - ***largely the same since tube diameter has been increased***

Thermal Considerations

Vapor Return Tube- Heat Gain

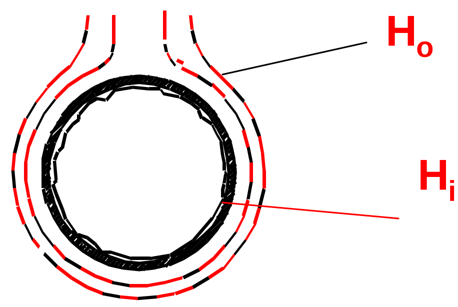
- Analysis objectives
  - ultimately establish fluid temperature as function path length
    - point at which dry vapor is attained in the return path, in terms of exit quality
    - fluid density and velocity for updating pressure drop calc's
  - iterate analysis information on tube thermal insulation and thermal boundary conditions become available
    - heat transport influenced by tube bundling arrangements, as well
  - provide information for refrigerant cycle analysis
- Initial step
  - solve for free convection heat transfer of isolated tube
    - bound heat gain
  - solve for heat transport for bundled tube arrangement using CFD code as required
    - establish reduction in heat gain from bundled arrangement and confines of walls

Thermal Considerations

Thermal Boundary and Heat Transfer Coefficient

- Approach-*Initial step*
  - evaluated free convective coefficient for isolated horizontal tube
  - inside film coefficient determined from flow parameters, velocity, etc., from fluid analysis
  - outside film coefficient based conventional method for determining free convection coefficient, i.e., ΔT between surface and surroundings, fluid buoyancy, etc.
  - solution of simultaneous equations
- *More detail needed*
  - *tube bundle arrangement*
    - *adjacent inlet and return lines?*
  - *orientation*
  - *proximity of walls--significant effect on free convection coefficient*

Isolated horizontal tube



reasonable for 1st cut

Multiple tubes bundled, tube shape?

No evaporation of a fluid, based on sensible heat gain only
to accurately determine at what point residual vapor is evaporated is the next step

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Return Vapor Line

Tubing Layout

(latest info courtesy of Eric Anderssen)

Location	Current Diameter	Desired Diameter	Length	Number Exhaust Tubes per side (nominally)		Bundle Dimension for desired tube size		Insulation Thickness	Exterior/Gas Temperature
				Stave	Disk	Inside	Outside	***dry gas***	
Pixel Envelope	7	7	0.01	3	3			***dry gas***	-10
Pixel Envelope	7	7	0.01	3	3			***dry gas***	-10
Pixel Envelope	7	7	0	3	3			***dry gas***	-10
Pixel Envelope	7	7	0.15	3	3			***dry gas***	-10
Pixel Envelope	7	7	0	3	3			***dry gas***	-10
Pixel Envelope	7	7	0.6	3	3			***dry gas***	-10
Leave Pixel Envelope	7	7	0.1	3	3			***dry gas***	-10
SCT Barrel	7	7	0.02	3	3			***dry gas***	-10
SCT Barrel	7	7	0	3	3			***dry gas***	-10
SCT Barrel	7	7	0.35	3	3			***dry gas***	-10
SCT Barrel	7	7	0.02	3	3			***dry gas***	-10
Leave Thermal Barrier	7	7	0.04	3	3			***dry gas***	-10
TRT Gap	7	7	0.5	3	3	21 X 14	31 X 24	5mm	20
PPB1	7	7	0	3	3			***dry gas***	20
PPB1	7 to 7	7 to 9	0.04	3	3			***dry gas***	20
PPB1	7	9	0	3	3			***dry gas***	20
Cryostat Bore	7	9	2.5	3	3	27 X 18	38 X 28	5mm	20
PPF1	7	9	0.3	3	3	27 X 18	38 X 28	5mm	20
Cryostat Side	7	9	2	3	3	27 X 18	38 X 28	5mm	25
Enter Tile nooses	7	9	0	3	3	27 X 18	38 X 28	5mm	25
Enter PPB2	7	9	0.2	3	3			***dry gas***	25
PPB2	7	9	0.3	3	3			***dry gas***	25
PPB2	7 to 13	9 to 13	0.05	3	3			***dry gas***	25
PPB2	13	13	0.3	3	3			***dry gas***	25

Total 2.2 m (uninsulated)

1.3 m

.04 m

.85 m

Total path length to this point of 7.5 m

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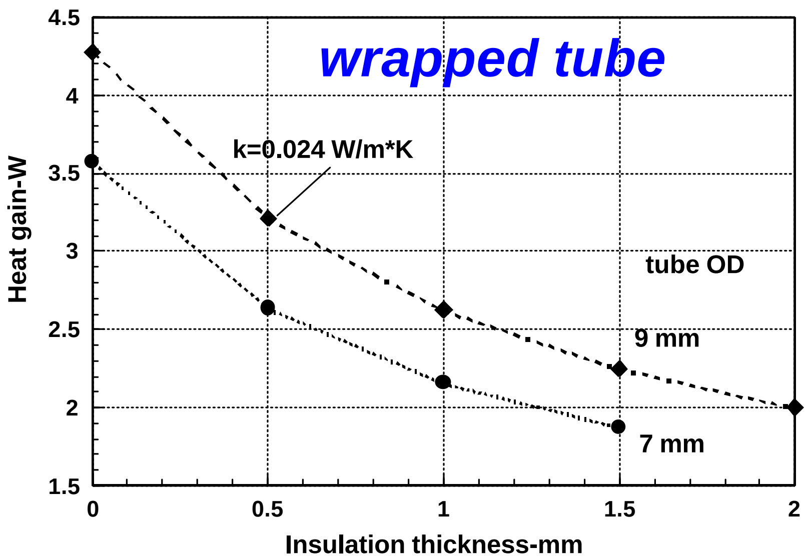
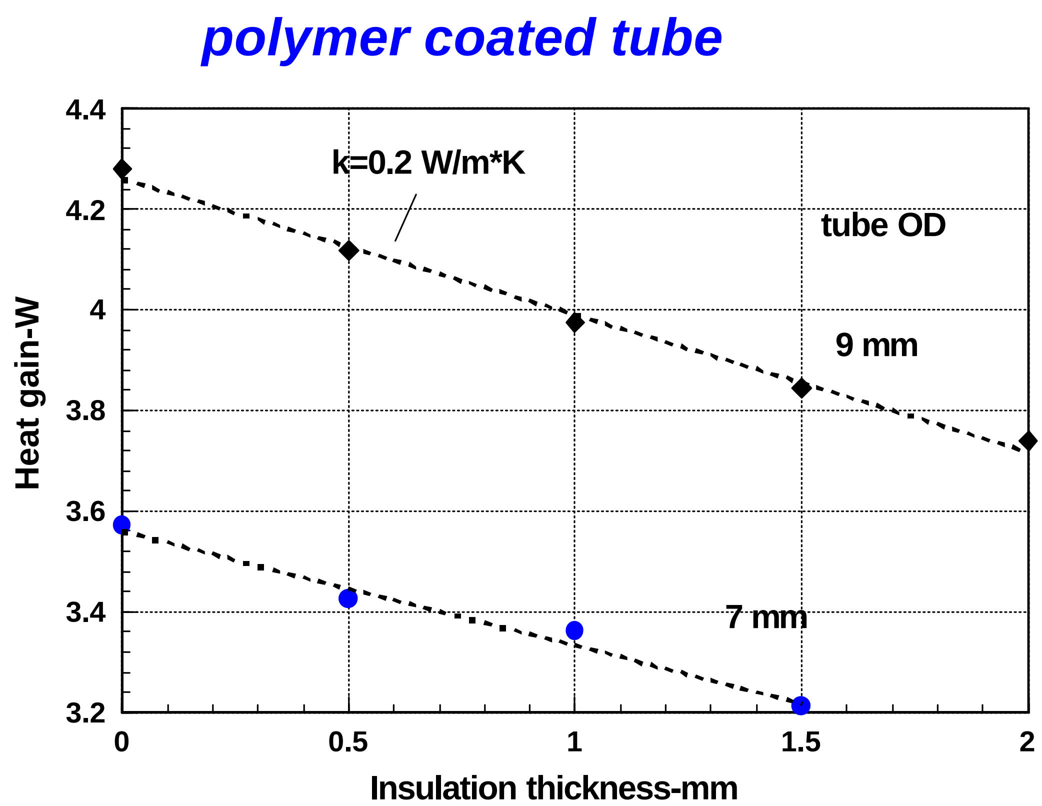
Insulation Analysis

Tube Heat Gain in Cold Space-*Isolated Tube* (-10ºC)

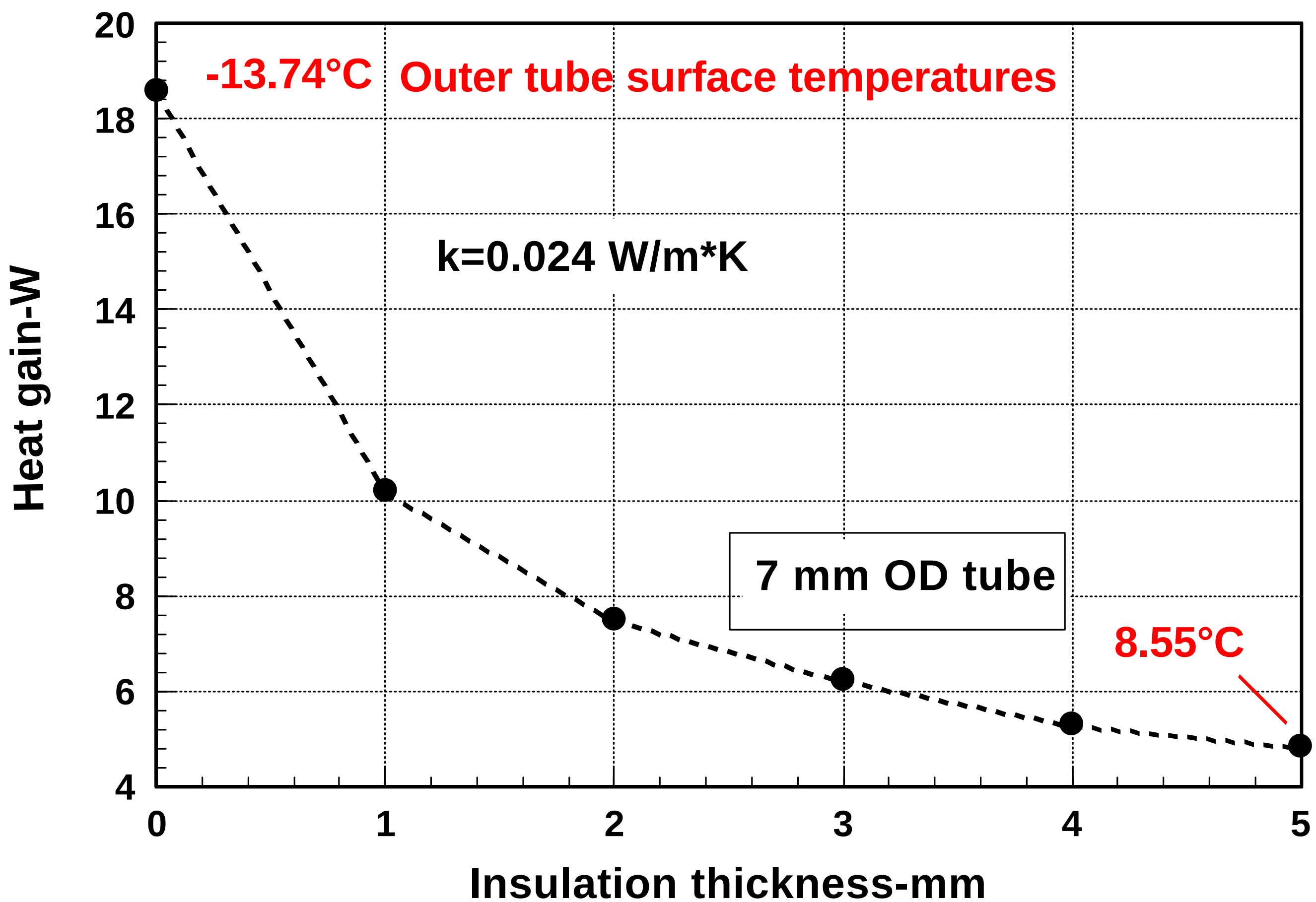
- *Effect of insulation*
  - wrap tube with simple insulation potentially cuts heat gain
  - creates dead nitrogen gas space

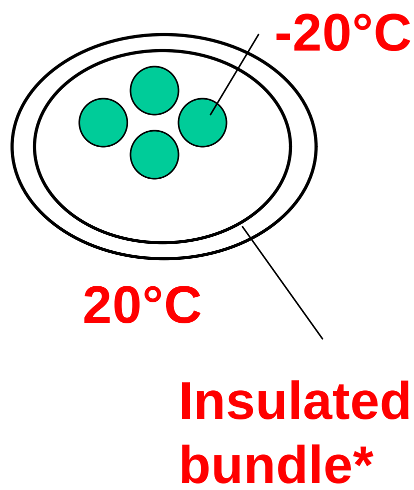




Tube Insulation Analysis

Tube Heat Gain in Warm Space-*Isolated Tube* (20ºC)





*very different concept

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Tube Insulation Analysis

Observations Based on First Cut

- Heat gain in Pixel/SCT cold region (-10ºC)
  - Uninsulated, unbundled tube will gain heat via free convection heat transfer
    - unless in close proximity to walls, which disrupts convection
  - An estimate of the sensible heat gain
    - 7 mm OD tube, 4.68 W/m, or 6.1 W in 1.3 meter run
    - Amounts to 3% heat gain within the thermal enclosure @ -10°C
      - based on 202 W, modularity of two
- Heat gain in TRT Gap to PPB2 (20ºC)
  - An estimate for same 7 mm, but insulated tube, 4.85 W/m, 5.3 meters, 25.7 W, or 12.7% gain @ 20 °C space temperature
  - Uninsulated portion for 7 mm, 18.8 W/m, 0.89 meters, 16.8 W, or 8.3% @ 20 °C space temperature
    - note tube surface temperature is -13.74°C
- Total vapor return tube heat gain *up to insulated tube region*
  - 48.6 W, or 24%--*may be lower depending on thermal boundary conditions, <u>however</u>*
    - *if totally sensible heat gain--<u>this mounts to 27.6°C increase</u>* in vapor temperature

Tube Insulation Analysis

Comments

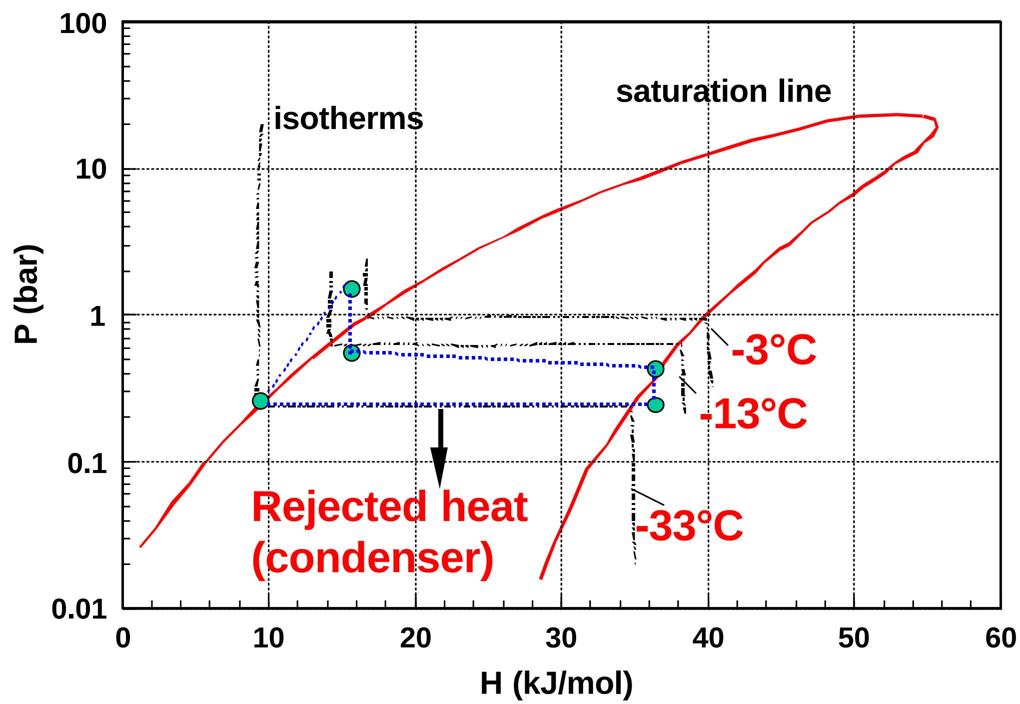
- **More work is needed, *but***
  - ***if fluid exits at a quality of 0.88, I.e., 12% excess cooling capacity per stave, then***
    - ***fluid can pick-up nominally 12% and remain constant in temperature***
      - ***question is over what distance is required to evaporate***
    - ***mitigating this remark is the extent which the tubes are isolated***
      - ***from pressure drop viewpoint it is desirable to have the fluid evaporate within the first 6 meters***
    - ***if dry vapor exits, the heat transfer solution must be iterated to find the fluid temperature as function of location***
      - ***as temperature increases the inside and outside film coefficients change significantly***
  - ***clearly, a significant effect on predictability exists from the physical constraints***
  - ***<u>Free</u> convective heat transfer coefficients determined for the isolated tube ranged from <10 to 18 W/m^2 K, which are by most standards quite high***

C_4F_{10} Condenser Concept

Objective-Low Pressure ~0.5 bar system

- System issues in low pressure return
  - requirement for 250 mbar minimum pressure at inlet of compressor
  - compounded by distance to compressor
  - need for two stage compression to provide 2 bar inlet pressure
- Condenser approach
  - minimum return pressure limited only by choice of condenser temperature T_{sat}
  - Choice of T_{sat} influenced by refrigeration power to reject heat back to ambient
  - ***location close to detector is still important***

C_4F_{10} Pressure-Enthalpy Curve



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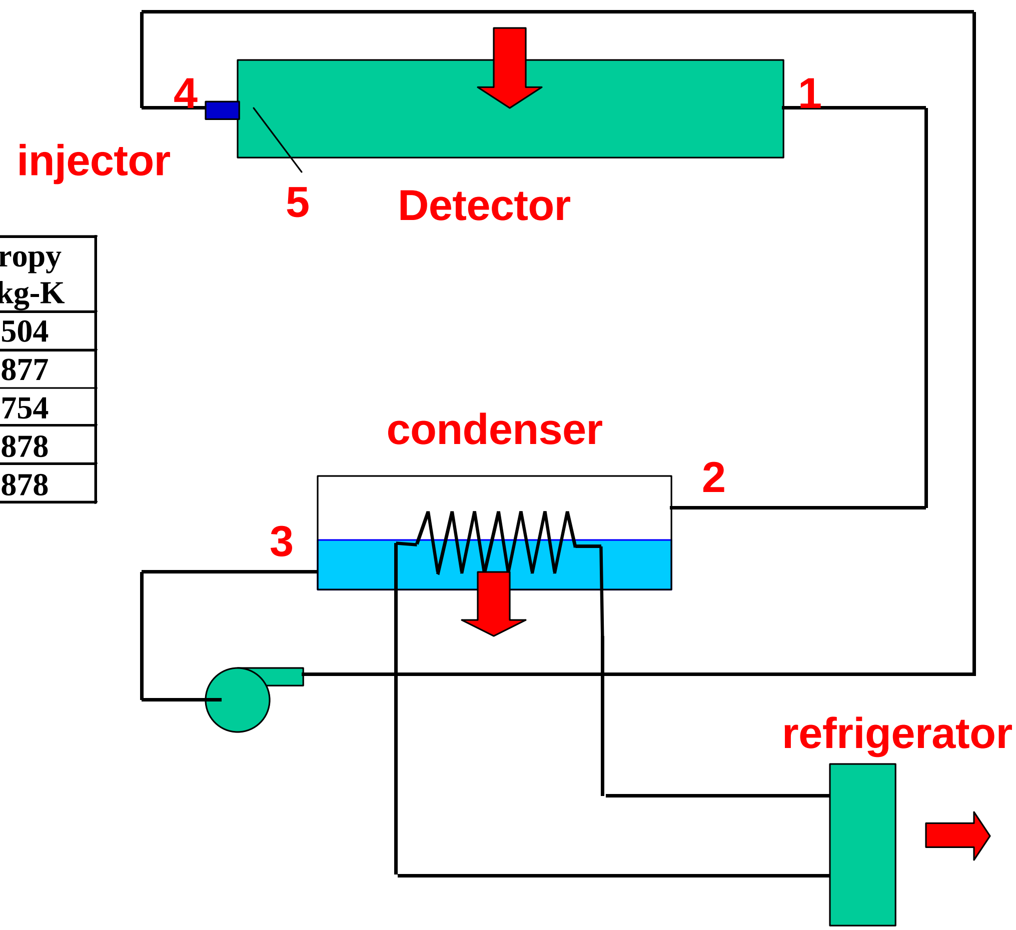
C_4F_{10} Condenser Concept

System Schematic

Referenced to T=200K

Point	Pressure mbar	Temperature Degree C	Enthalpy kJ/kg	Entropy KJ/kg-K
1	0.45	-20.5	154.02	0.1504
2	0.238	25	190.521	0.1877
3	.238	-33	38.529	0.1754
4	1.965	-5	67.029	0.2878
5	0.58	-15	67.029	0.2878



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C_4F_{10} Condenser Concept

Example Schematic-Arbitrarily Worst Case Scenario

- Comments
  - No attempt to avoid vapor return temperature reaching 25°C
  - Presumes injector temperature of -5°C
  - Pressure drop, PT 5 to PT 1, based on two phase calculation for a stave
  - Specified pressure of 238 mbar at condenser inlet is arbitrary
- Results
  - Heat input from, PT 5 to PT 1, is 86.99 kJ/kg
    - if quality X_o equals 1 at exit, all heat addition is from detector
    - X_o <1, then some heat is picked-up within the detector space
  - Maximum heat gain in return line PT 1 to PT 2 is 36.5 kJ/kg
  - Maximum heat input to return liquid to -5 °C, PT 3 to PT 4, 28.5 kJ/kg
  - Result forces condenser to remove, PT 2to PT 3, 151.99 kJ/kg
    - for 15 kW system, condenser rejects 151.99 kJ/kg, or 74.7% more heat than required (11.21 kW excess)
    - optimization of the heat cycle can improve this situation
      - colder inlet to injector
      - thermal isolation of vapor return lines or auxiliary cooling

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Analysis Status

What We Would Propose At This Stage-*More Work!*

- Refine cooling cycle analysis
  - predict heat transport in thermostructures
    - establish quality and margin for *dry-out*
    - assess benefit of increasing thermostructure hydraulic diameter for improved heat transport
  - evaluate refrigerator cycle required to pump heat out
    - re-evaluate condenser temperature and return vapor temperature
  - detail analysis of heat transfer associated with vapor and inlet lines to account for heat pick-up and determination of line insulation
    - thermal interaction of cold and warm lines due to their proximity
    - may be more optimum in long tube runs to effectively maintain fluid temperature by secondary cooling loop, e.g., water/methanol
- Full scale experimental mock-up of coolant system
  - Provide semblance of representative operational states for all elements
  - Demonstrate operating parameters for each element
  - compare experimental results with predictions

Summary Remarks

Issues Remaining for C_4F_{10} System

- Need to add confidence to the experimental base established to date on the low pressure C_4F_{10} system
  - not clear that a compressor at 140 meters would be acceptable, more analysis is needed
    - need information on required compressor pumping speed
    - results obtained thus far suggest
      - continue investigation of both systems, by adding more detail to the thermal hydraulic analysis
  - *refine the proposed condenser concept*
    - factor in reality of servicing, maintenance considerations
    - ensure mass accumulation in condenser system will not become a problem
      - centrifugal pump with pressure relief approach
    - condenser sizing
    - need for removing non-condensible gas accumulation?
  - refrigeration system requirements-for condenser concept
    - satisfy heat rejection at -33 °C
    - evaluate option of higher condenser temperature

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