BNL-99374-2013-TECH
C-A/AP/224;BNL-99374-2013-IR

Analysis and Design of Cold Helium Gas Warm Up for the 2K Experiment

A. Sidi-Yekhlef

November 2005

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC)

DISCLAIMER

C-A/AP/#224
November 2005

Analysis and Design of Cold Helium Gas Warm Up for the 2K Experiment

Olive Stohlman – Carnegie Melon University
John Krupczak, Jr. – Hope College
Ahmed Sidi-Yekhlef – Brookhaven National Laboratory

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

Analysis and Design of Cold Helium Gas Warm Up for the 2K Experiment

Olive Stohlman
Carnegie Melon University

John Krupczak, Jr.
Hope College

Ahmed Sidi-Yekhlef
Brookhaven National Laboratory

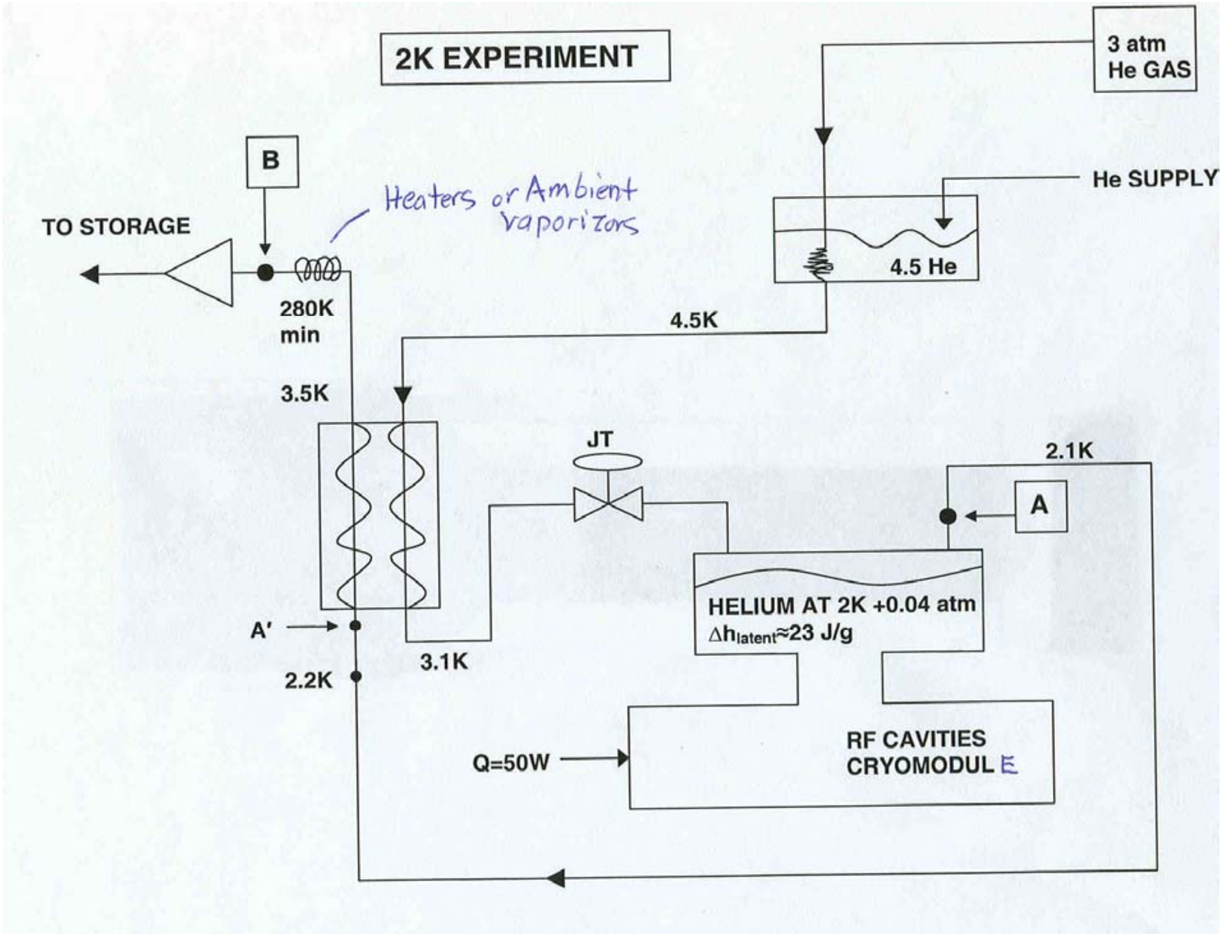
November 11, 2005

Overview

This file models the heating of helium gas from 11 K to a goal of at least 280 K. The purpose is to demonstrate the feasibility of an ambient vaporizer for this application, given the low pressure drop available.

The setup is a 100-foot Schedule 20 10” steel pipe leading into a vaporizer with some number of parallel, finned 1” pipes.

Results suggest that the proposed setup with 18 parallel vaporizer tubes will suffice, under the condition that about half of the leading 10” pipe be ice-free and open to natural convection. This section is pipe is valuable for the larger part of the heating operation and requires little pressure drop to maintain an acceptable flow rate. It is still advantageous to have a significant portion of the warm-up occur in the ambient vaporizer bank, because the cold gas demands less pressure drop to move through the pipe- thus, the more heating done at the end of the gas’s travel, the less pressure drop needed.



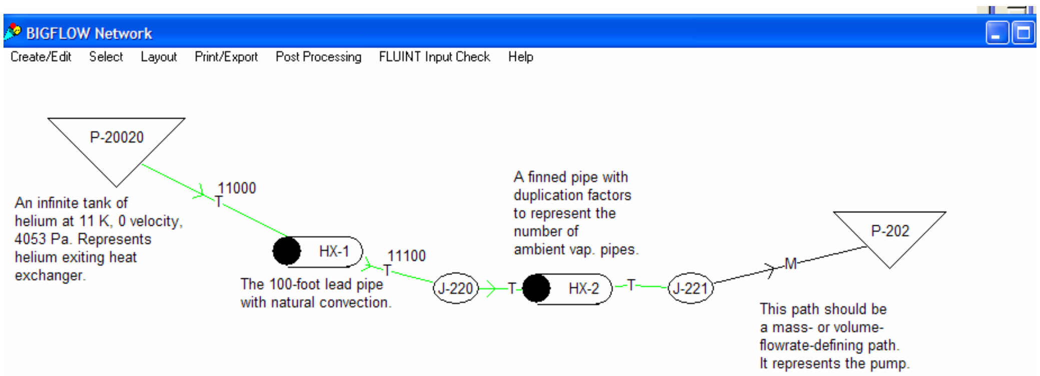
System Schematic

Model Structure

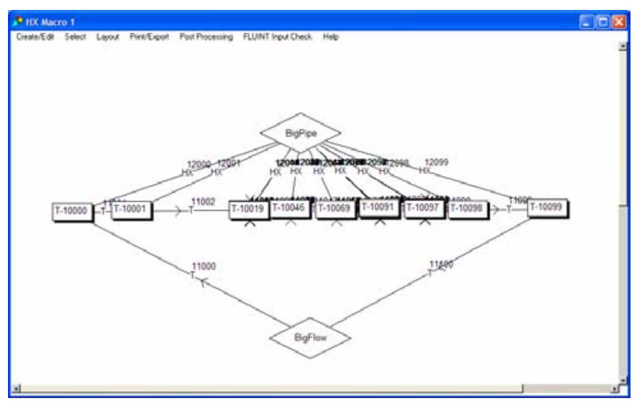
There are currently four submodels to this simulation: one fluid submodel (containing two HX macros), and three thermal submodels- the 10" tube, an ambient vaporizer tube, and a fin.

BigFlow

The fluid submodel, "BigFlow," defines the starting conditions and pumping conditions of the helium. Currently, the pump is modeled as a defined mass flow rate, rather than any complex pumping relationship between pressure and volume flow rate. This allows us to find plausible steady-state combinations of pressure drop, temperature, and mass flow.



The "HX-1" macro is the 10" pipe with natural convection. The "HX-2" macro is a single pipe of the ambient vaporizer; a duplication factor is applied at both ends to represent a bank of some number of pipes.



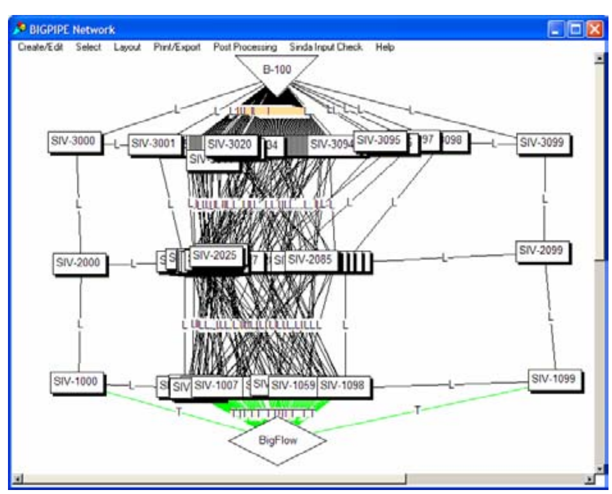
HX-1 and BigPipe

HX-1 connects to the thermal submodel "BigPipe," a three-layer, 100-axial division model of the steel pipe wall. Thermal properties (heat capacity and thermal conductivity) of the steel are calculated from arrays of temperature, property pairs (arrays 1 and 2, respectively, of the submodel).

Convection between the pipe and wall is calculated by FLUINT.

Axial and radial conduction within the pipe wall model are calculated with standard formulas. The subroutine "NCHCT" calculates a separate convection coefficient for each out-layer lump of the wall. (This subroutine is based on natural convection from a horizontal cylinder.)

Simulations showed that the outer layer of the metal, if open to free convection, was generally above 200 K in temperature.

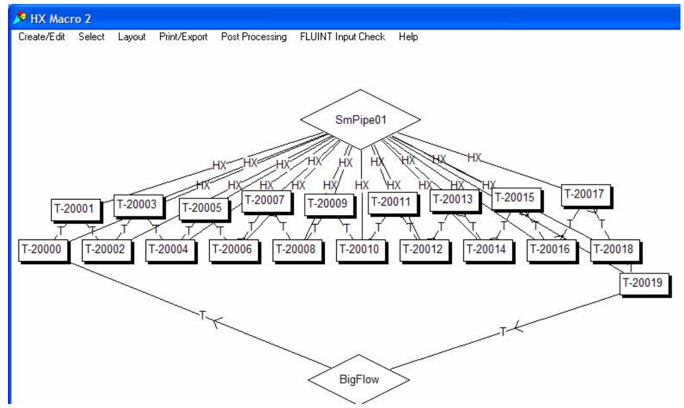


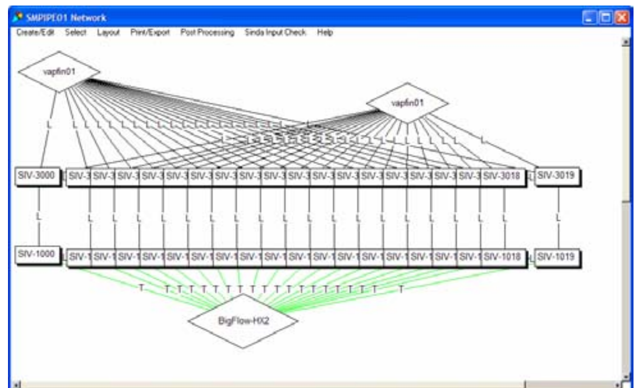
HX-2, SmPipe01, and vapfin01

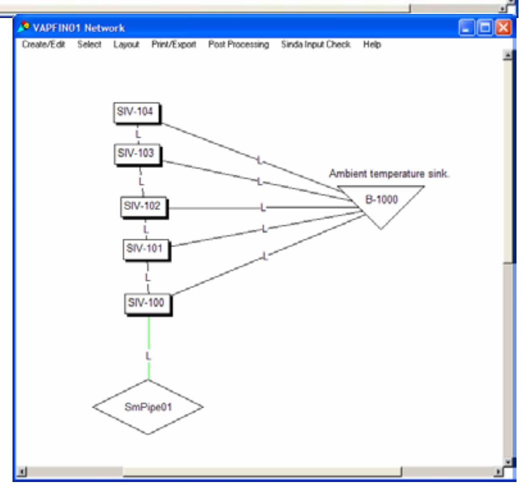
The HX-2 macro is duplicated according to the register “sp_rep.” it represents a single pipe of the ambient vaporizer, made of aluminum.

No convection directly off the pipe wall is included. All heat exchanged with the environment is done through the fin model “vapfin01,” and the heat exchange seen by the tube is multiplied by the number of fins defined by the register “fins_per.”

Vapfin01 represents five long, vertical stripes of metal along the fin. Because heat exchange from a vertical plate is not a linear function of height, it is unfortunately necessary to assume a single temperature along each of these stripes. The five subdivisions exist because SINDA has no subroutine for fin efficiency. Each fin is assumed to be standing alone in the ambient environment. Calculations of the netual convection off the fins are done is “Variables 1” of the fin submodel.







Assumptions

- no losses in fittings
- identical parallel tubes is ambient vaporizer
- identical fins
- fins are free standing flat plates with vertical stripes of constant temperature
- pump represented as constant mass or volume flow rate
- ice either completely blocks a give section of pipe or has no effect at all.

Future Improvements

K factor of pipe splitting
- from pg. A-29, Crane: $60f_T$ for a sharp 90-degree bend
- from pg. A-29, Crane: f_T=0.014 for 10-inch pipe
- K=0.84

Could be included in the "FK" field of the entrance path to the HX submodel for the ambient vaporizer

- Other loss factors
- More complex feed system model
- More fluid properties down to correct start temperature (Complete property tables were only available down to 11 K, with an always-gas assumptions) (Current properties from Cullimore & Ring)
- account for interaction between fins

Registers

sp_* : Registers related to the pipes in the ambient vaporizer
k* : Equations for conduction factors (A/x, radial conduction)
fin_* : Fin properties
T* : Temperatures

AFLOW	PI/4*ID^2		Flow area
CAVVOL		1	Volume of experiment-cooling tank
DRATIO		8	Ratio of middle lump wall thickness to inner/outer lump wall thickness
FINS_PER		4	number of fins per tube section
FIN_HEI		4.572	vertical height of fins (longest dimension)
FIN_LEN		0.1016	radial extension of fins
FIN_SUBD		5	number of lumps to represent fin
FIN_WID		0.0025	width of fins (smallest dimension)
HEATING		50	Heat produced by experiment in tank (W)
ID		0.2545	Inner diameter of pipe
KAX_IM	2*PI*LN(((MD1+MD2)/2)/ID)*LENGTH/NUM		Radial conduction from inner to middle ring
KAX_MO	2*PI*LN(OD/((MD1+MD2)/2))*LENGTH/NUM		Radial conduction from middle to outer ring
KLONG_I	PI/4*(MD1^2-ID^2)/(LENGTH/NUM)		longitudinal conduction along inner ring
KLONG_M	PI/4*(MD2^2-MD1^2)/(LENGTH/NUM)		longitudinal conduction along middle ring of pipe
KLONG_O	PI/4*(OD^2-MD2^2)/(LENGTH/NUM)		longitudinal conduction along outer ring of pipe
LENGTH		30.5	pipe length (m)
MD1	1/(2+DRATIO)*(OD+(1+DRATIO)*ID)		
MD2	OD+ID-MD1		
MFLOW		0.0022	constant mass flow rate
INT:NUM		100	number of longitudinal subdivisions
OD		0.273	Outer diameter of pipe
PCAV		4053	Start pressure of experiment tank
PDENS		1	density of pipe material
PFEED	PCAV		
PIE	PI		pi
PLAB		101325	Pressure in room outside pipe
PSUCT	PFEED-266		Suction pressure
PWROUGH	0.00005/ID		Relative wall roughness
P_A	PFEED		Pressure after 1st heat exchanger
SP_CSA	PI/4*(SP_OD^2-SP_ID^2)		metal cross-section of finned pipes
SP_DENS		2770	density of small pipe material
SP_DIV		20	
SP_FLOWA	PI/4*SP_ID^2		
SP_ID		0.0254	Inner diameter of small pipe (pipe with fins)
SP_KLONG	PI/4*(SP_OD^2-SP_ID^2)/(2*SP_LEN/SP_DIV)		axial conduction k factor
SP_KRAD	2*PI*LN(SP_OD/SP_ID)*SP_LEN/SP_DIV		Radial conduction k factor
SP_LEN	FIN_HEI		length of small pipe
SP_OD		0.0264	Outer diameter of small pipe (pipe with fins)
SP_REP		48	total number of parallel finned pipes
SP_ROUGH	0.0000015/SP_ID		
TFEED		11	
TFINISH		280	Temperature of final plenum
TLAB		298	Temperature of room outside pipe
TSTART_I		100	start temperature of inner pipe layer
TSTART_M		200	start temperature of middle of pipe
TSTART_O		298	start temperature of outside of pipe
T_A		11	Temperature after first heat exchanger
VFLOW		0.32	constant volume flow rate
VIN	PI/4*(MD1^2-ID^2)/NUM		volume of each inner pipe lump
VMID	PI/4*(MD2^2-MD1^2)/NUM		volume of each middle pipe lump
VOUTER	PI/4*(OD^2-MD2^2)/NUM		volume of each outer pipe lump

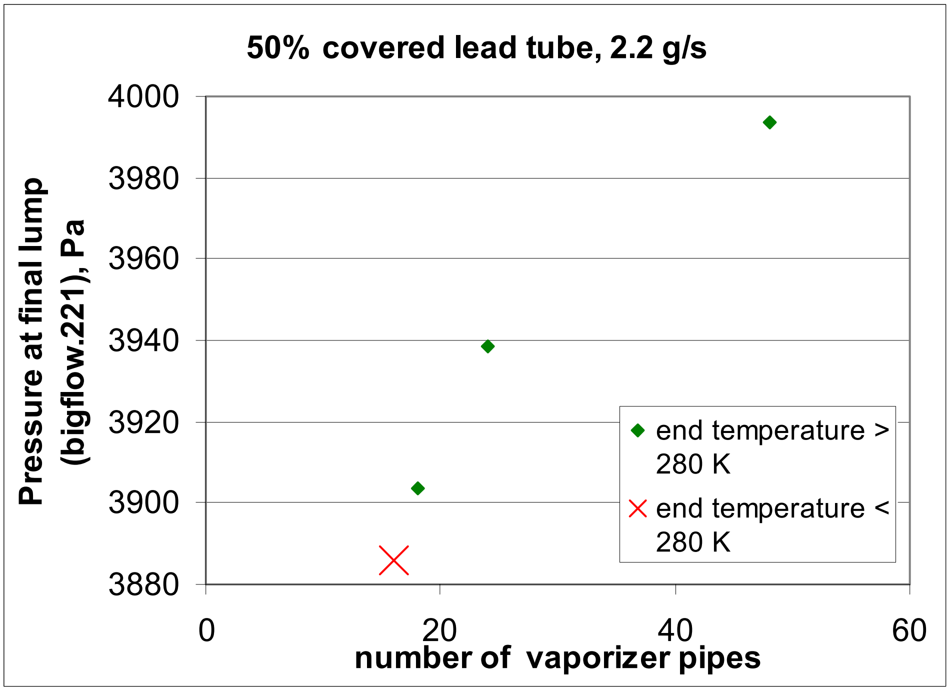
AFLOW: Cross-section flow area on 10” pipe
ID: The inner diameter (in meters) of the 10” pipe
DRATIO: The ratio of the thickness of the inner and outer layers of the 10” pipe to the center layer. The outer layers were made thinner for temperature accuracy.
HEATING: Not currently in use; would be the steady-state rate of heat generation by the experiment. (A previous model had an experiment tank connected to a feed plenum; these were removed to simply the model.)
KAX_IM: $= 2\pi \cdot \ln\left(\frac{MD1 + MD2}{2 \cdot ID}\right)$ This is the standard formula for conduction between two radial levels. It calculates this for the inner two levels of the 10” pipe
LENGTH: Length of 10” tube (assumed to be 100 feet).
MFLOW: When the final path (21022) in the BigPipe model is a mass flow rate-defining path, this value can be used to specify the mass flow rate (in kg/s)
NUM: The number of axial lumps on the BigPipe model (this cannot be changed dynamically; the lumps must be added or removed by hand to match this number if it is changed!)
OD: The outer diameter (in meters) of the 10” pipe
P_A: The pressure in the source plenum
PCAV: In a previous version of the model, this was the pressure in the experimental cavity.
PFEED: In a previous version of the model, this was the pressure of the helium source feeding into the experiment cavity.
PIE: FORTRAN doesn’t understand “pi.”
PLAB: The ambient pressure is used in natural convection calculations only.
PSUCT: In a previous model, there was a fixed suction pressure. This was impractical as a pump model, but this value is still used in the end plenum.
PWROUGH: Pipe wall relative roughness for the 10” (Schedule 20) pipe
SP_CSA: The cross-sectional area of the metal annulus in the vaporizer pipes is used to calculate axial heat transfer and volume.
SP_REP: This is one of the most important user-adjusted values. This determines the number of parallel vaporizer pipes, each of which will experience identical fluid flow. Fractions are acceptable, but I don’t know why you would do that.
SP_DIV: See “NUM.”
TSTART_*: These values do not effect the steady-state results.
T_A: The temperature of the source plenum.
VFLOW: When the final path (21022) in the BigPipe model is a volume flow rate-defining path, this values can be used to specify the volume flow rate (in m^3/s)
VMID: The volume of each lump of the central cylinder of the 10” pipe

Trial Runs

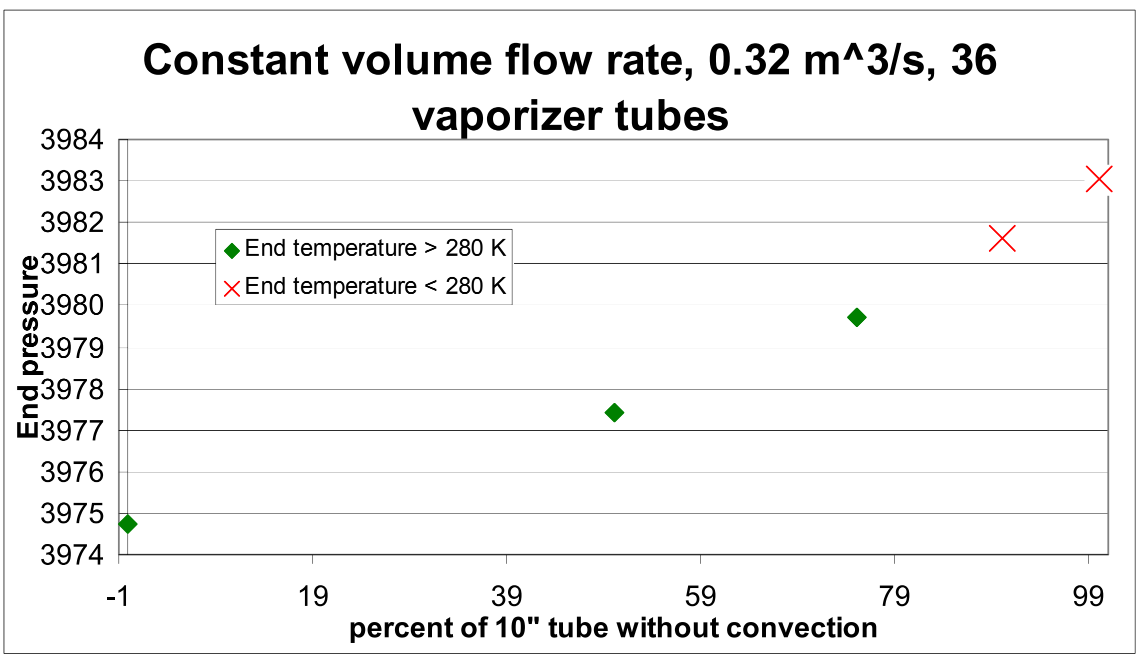
	pipes	Pressure at end junction (Pa) (tank BigFlow.221, immediately before the "pump")	Temperature at end junction (K)	Temperature in first lump of fin bank (K)	Mass flow rate (g/s)	Volume flow rate (m^3/s)
Limits	12	>3800	>280		>2	
Full lead tube convection	12	3777.51	285.94	263.196	2.52874	0.40
Full lead tube convection	12	3826.49	291.707	278.411	2.00895	0.32
No lead tube convection	12	3883.25	239.11	51.5726	2.4836	0.32
No lead tube convection	12	3910.75	249.625	66.1659	1.8724	0.25
No lead tube convection	36	3983.05	272.172	134.27	2.24	0.32
No lead tube convection	36	3985.4	272.936	137.731	2.15147	0.308
Lead tube convection for nodes 50+	36	3979.93	288.835	252.556	2.03103	0.308
50+	36	3977.43	287.547	248.669	2.11826	0.32
90+	36	3981.6	276.32	167.969	2.20599	0.32
75+	36	3979.73	281.6	206.672	2.16388	0.32
Full lead tube convection	36	3974.73	293.945	283.726	2.07106	0.32
Mass flow set (not volume), 50+	12	3843.26	276.669	224.294	2.1	
Mass flow, 50+	24	3942.92	284.404	239.3	2.1	
Mass flow, 50+	18	3903.45	280.276	227.695	2.2	
Mass flow, 50+	16	3885.97	279.183	225.141	2.2	
Mass flow, 50+	48	3993.59	288.915	252.995	2.2	
Mass flow, 50+	24	3938.57	283.346	234.706	2.2	

Register Data for above chart

```
REGISTER DATA (for trial runs)
       AFLOW = PI/4*ID^2 $ Flow area
       VFLOW = 0.32 $ constant volume flow rate
       PIE = PI $ pi
       T_A = 11 $ Temperature after first heat exchanger
       P_A = PFEED $ Pressure after 1st heat exchanger
       CAVVOL = 1 $ Volume of experiment-cooling tank
       DRATIO = 8.0 $ Ratio of middle lump wall thickness to inner/outer lump wall thickness
       FINS_PER = 4 $ number of fins per tube section
       FIN_HEI = 4.57200  $ vertical height of fins (longest dimension)
       FIN_LEN = 0.1016 $ radial extension of fins
       FIN_SUBD = 5 $ number of lumps to represent fin
       FIN_WID = 0.0025 $ width of fins (smallest dimension)
       HEATING = 50 $ Heat produed by experiment in tank (W)
       ID = 0.2545 $ Inner diameter of pipe
       KAX_IM = 2*PI*LN(((MD1+MD2)/2)/ID)*LENGTH/NUM $ Radial conduction from inner to middle ring
       KAX_MO = 2*PI*LN(OD/((MD1+MD2)/2))*LENGTH/NUM $ Radial conduction from middle to outer ring
       KLONG_I = PI/4*(MD1^2-ID^2)/(LENGTH/NUM) $ longitudinal conduction along inner ring
       KLONG_M = PI/4*(MD2^2-MD1^2)/(LENGTH/NUM) $ longitudinal conduction along middle ring of pipe
       KLONG_O = PI/4*(OD^2-MD2^2)/(LENGTH/NUM) $ longitudinal conduction along outer ring of pipe
       LENGTH = 30.5 $ pipe length (m)
       MD1 = 1/(2+DRATIO)*(OD+(1+DRATIO)*ID)
       MD2 = OD+ID-MD1
       INT:NUM = 100 $ number of longitudinal subdivisions
       OD = 0.2730 $ Outer diameter of pipe
       PCAV = 4053 $ Start pressure of experiment tank
       PDENS = 1 $ density of pipe material
       PFEED = PCAV
       PLAB = 101325  $ Pressure in room outside pipe
       PSUCT = PFEED-266 $ Suction pressure
       PWROUGH = 0.00005/ID $ Relative wall roughness
       SP_CSA = PI/4*(SP_OD^2-SP_ID^2) $ metal cross-section of finned pipes
       SP_DENS = 2770 $ density of small pipe material
       SP_DIV = 20
       SP_FLOWA = PI/4*SP_ID^2
       SP_ID = 0.0254 $ Inner diameter of small pipe (pipe with fins)
       SP_KLONG = PI/4*(SP_OD^2-SP_ID^2)/(2*SP_LEN/SP_DIV) $ axial conduction k factor
       SP_KRAD = 2*PI*LN(SP_OD/SP_ID)*SP_LEN/SP_DIV $ Radial conduction k factor
       SP_LEN = FIN_HEI $ length of small pipe
       SP_OD = 0.0264 $ Outer diameter of small pipe (pipe with fins)
       SP_REP = 12 $ total number of parallel finned pipes
       SP_ROUGH = 0.0000015/SP_ID
       TFEED = 11
       TFINISH = 280 $ Temperature of final plenum
       TLAB = 298.0 $ Temperature of room outside pipe
       TSTART_I = 100.0 $ start temperature of inner pipe layer
       TSTART_M = 200.0 $ start temperature of middle of pipe
       TSTART_O = 298.0 $ start temperature of outside of pipe
       VIN = PI/4*(MD1^2-ID^2)/NUM $ volume of each inner pipe lump
       VMID = PI/4*(MD2^2-MD1^2)/NUM $ volume of each middle pipe lump
       VOUTER = PI/4*(OD^2-MD2^2)/NUM $ volume of each outer pipe lump
```



This graph shows different numbers of parallel vaporizer pipes and the resulting final pressures. Higher final pressure indicate lower pressure drops. There was a constant mass flow rate of 2.2 g/s.



This graph shows how less pressure drop is needed if more of the 10” tube has no convection (or is iced), but that there is a cutoff around 75% after which 36 ambient vaporizer tubes cannot heat the gas sufficiently.

References

Crane Co, Flow of Fluids Through Valves, Fittings, and Pipe (Technical Paper No. 410 M). New York, 1986

Cullimore and Ring Technologies, Inc. http://www.crtech.com/properties.html . 2003: Helium properties, air properties.

Fox, R. and McDonald, A. Introduction to Fluid Mechanics, 5th ed. Wiley.

Holman, J.P. Heat Transfer, 9th ed. 2001: McGraw-Hill