Fermi National Accelerator Laboratory

FERMILAB-Pub-93/371

Special Gas Heater for the Tesla Test Facility

Ronald J. Walker, Gary Hodge and Jagir S. Reehal

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

December 1993

To be published in *Advances in Cryogenic Engineering*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

SPECIAL GAS HEATER FOR THE TESLA TEST FACILITY

Ronald J. Walker, Gary Hodge, and Jagir S. Reehal

Fermi National Accelerator Laboratory *
Batavia Illinois 60510

ABSTRACT

A special heater has been designed and is under construction at Fermi National Accelerator Laboratory for use at the TESLA test facility at the Deutches Electronen Synchrotron (DESY). This heater is used to warm up the 2.2 K helium gas coming from a dewar which is being pumped down to a pressure of 1600 Pa in order to keep the liquid in the test dewar in the superfluid state. This heater must warm the gas from 2.2 K to 300 K and must have a sufficiently low flow restriction that the pressure drop is less than 100 Pa across the unit with a flow of 10 grams/second. The heating element is constructed of 304 SS tubes with diameter .0127 m and wall thickness 0.254 mm. Each tube is 1 meter long and there are 648 tubes arranged in a square bundle. The tubes are heliarc welded to 3.176 mm thick stainless bars which make the electrical connections to the tubes. The gas is heated primarily inside the tubes with electrical current. The tubes are in a series parallel electrical arrangement which requires a power supply current of 500 amperes. A test has been performed which determines the performance of a single tube for a family of values flow and heating which bring helium gas from 77 K to 300 K. The results of the test will be compared with a computer simulation of the performance of a single tube.

INTRODUCTION

Fermilab is participating in the international collaboration called TESLA. This project is to build two linear accelerators with superfluid liquid helium cooled radio frequency accelerating cavities. The accelerators will produce head on collisions of electrons and positrons at an energy of 500 Gev.

A large amount of development is in progress at DESY (Deutches Electronen Synchrotron.) A part of this development will be a hall

---

* Research sponsored by the Universities Research Association, Inc. under contract with the U.S. Department of Energy.

containing a number of vertical and horizontal dewars to test cavity strings in superfluid liquid helium baths. A special heater is needed to warm boiloff gas from these 1.8 K tests to ambient temperature prior to entering the vacuum pump.

Typically the saturation pressure above the superfluid bath is 1600 Pa. Since the gas pressure is so low, it is necessary to have a pressure drop across the heating element of 100 Pa or less in order to maintain the flow through the pump. Another consequence of the low pressure is that we felt that it was necessary to perform flow tests to verify the pressure drop correlations and the heat exchange correlations that were used to design the heating element.

A major hurdle to overcome in this project is to provide the pressure vessel with a German code qualification. In addition the pressure vessel has an ASME code stamp so that it can be tested at Fermilab.

The pressure vessel was fabricated by Cryenco in Denver Colorado. An insulating vacuum jacked is to be attached to the inner coded pressure vessel to prevent frosting of the shell at the cold end of the vessel. This jacket is being manufactured at Fermilab and will be welded to a flange on the side of the pressure vessel. This procedure will not void the code stamping of the pressure vessel.

DESIGN OF THE PRESSURE VESSEL

The pressure vessel contains the heater element. Cold helium gas at a pressure of 1600 Pa enters at a vacuum break at the bottom . There is a stress relief section in the incoming piping designed to relieve stresses created by the shrinking of parts of the vessel as they cool down.

The code requirements are that the maximum allowable internal working pressure is 202.7 kPa (two atmospheres).

Figure 1 shows the main parts of the pressure vessel. The vessel comes apart at the top to access the element.

The seal for the flange is special because of the low design operating pressure. This pressure is 1.6 kPa. Because of the low pressure, extra precautions were taken with the seal. The seal consists of two concentric rubber "O" rings with a guard pressure of helium gas maintained between the two seals. The pressure of the guard helium is slightly above atmospheric pressure to prevent air leaking in, which would cause plugging problems in the system refrigerator.

The same precautions were taken with the seals where the copper current busses penetrate the top head. In this case, the rubber 'O" rings are radial seals (double) on both the inside diameter and outside diameter of a nylon bushing which serves as an electric insulator.

Ceramic seals were used for the instrumentation feed through.

The heated gas, approximately at ambient temperature, comes out through a 25.4 cm (10 inch) pipe shown as a head on circle in the figure.

DESIGN OF THE HEATER ELEMENT

In order to design the heater element, a good starting point is to select correlations for heat transfer and pressure drops in heated tubes. The correlations selected were from a reference text book.[1] The correlations are as follows (see the NOTATION section at the end of the paper).

$$\frac{\Delta p}{\Delta L} = 32G^2/(\mathrm{Re}\ D\ \ \rho)$$

$$h = \left[3.658 + \frac{0.0668(D\ /L)Re\ Pr}{(1+0.04)[(D\ /L)Re\ Pr]^{2/3}} \right] \frac{k}{D}$$

The above correlations are for fully laminar flow, which is the case for all of the calculations involved.

In order to determine the sizing of the tubes, a computer program was written in VAX fortran. The program proceeds in steps from the cold end toward the warm end. To get started, the wall temperature in the first segment is assumed to be the temperature of the cold gas. The wall temperature is then calculated using the equation above for h and equating the heating in the segment from the current to the heat transferred from the tube wall. This will yield a value of ΔT from the equation

$$Q_I = h\ A\ \Delta T$$

Using this ΔT as the temperature difference from the gas in the first segment (or any segment) will give an new estimate for the wall temperature. The temperature used to evaluate the heat transfer

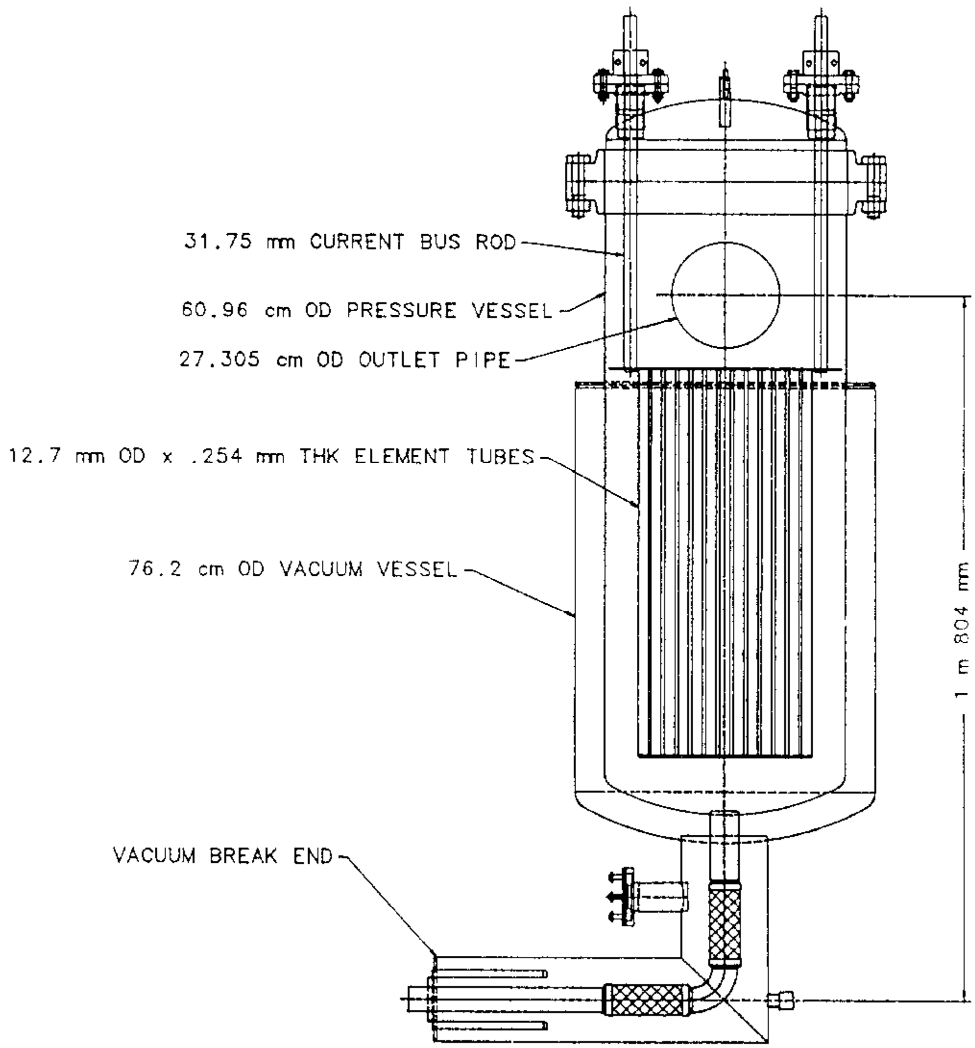

Figure 1. Vertical sectional drawing of the heater assembly

coefficient h in the above correlations is the mean between the gas and wall temperatures. An iteration of 10 replacements of the wall temperature converges quickly to give a final wall temperature in the segment.

To compute the heat generated in the segment, stainless steel type 304 resistivity was taken from Van Sciver[2]. Helium gas properties were from a package called HEPAK from Cryodata Corp.

To complete the calculation in the segment, the gas enthalpy was updated using the relation

$$\Delta H \frac{dm}{dt} = Q_I$$

The pressure was updated using the pressure drop correlation above. The program then steps to the top of the tube.

The calculation described above does not include effects of thermal conduction down the tube. The effects of conduction in the thin wall tubing is not critical to the overall heating effect, sizing of tubing and number of tubes needed. When analyzing the test of correlations and interpreting temperature measurements at discrete points on a test tube, it will be necessary to include conduction effects. Table 1 gives the specifications decided on using the program described above. Note that the inlet temperature, outlet temperature, and pressure drop are the same for both the whole tube bundle and a single tube, and the gas flow goes through all the tubes in parallel.

To make the heater practical, it is necessary to produce a series electrical arrangement of tubes because all the tubes in parallel electrically would require a current of 11923 amperes. This is accomplished by welding 27 tubes on the end into a 304 SS bar that is 3.333 cm wide by .3175 cm thick(1/8 inch). These bars cross the current over to the next row of tubes at the top or bottom to form a series arrangement of parallel groups of 27 tubes. With this arrangement, the total current is only 496.8 amperes as shown in Table 1.

Table 1. Heater element specifications

Single tube characteristics	value	unit
alloy	304 SS	
diameter	1.27	cm (.5 in)
wall thickness	.0254	cm (.01 in)
length	1	m
current	18.4	A
voltage	1.314	V
power dissipated	24.17	W
resistance	.0714	Ω
design mass flow	.01543	g/s
helium inlet temperature	3	K
helium outlet temperature	300.5	K
pressure drop	61.94	Pa
inlet pressure	1.6	kPa
Tube bundle characteristics		
total number of tubes	648	
number of tubes per parallel bank	27	
number of parallel banks in series	24	
voltage	31.5	V
current	496.8	A
power	15649	W
mass flow	10	g/s

Figure 2 shows a photograph of the element assembly on its side in construction. Note the cross over plates and half moon shape plate that contains the buss bar connection and only one row of tubes.

TESTS OF HEAT EXCHANGE AND PRESSURE DROP CORRELATIONS

A preliminary to actually checking the heat exchange was to run a resistivity measurement on the tubing. The data obtained for resistivity is shown in Figure 3. The smooth curve is a quadratic least squares fit to the data.

$$\text{resistivity} = A_1 + A_2\,T + A_3\,T^2$$

$$A_1 = 4.85823\times10^{-7} \qquad A_2 = 1.20094\times10^{-9} \qquad A_3 = -4.4388\times10^{-13}$$

The tubing used for the tests of he correlations in the pressure range of 1.6 kPa. was 321 SS with .9525 cm (3/8 inch) diameter, .01524 cm (.006 inch) wall thickness, and 50.64 cm long. The tubing was warmed from about 80 K to about 300 K during the tests. Mass flow in the tube ranged from .0064 to .004 g/s in the helium test and from .0121 to ,0208 g/s in the nitrogen tests.

The heated tube was in a vacuum pipe and fitted with 5 very precise and small type T (copper constantan) thermocouples. The gas flow is inside the tube. Insulating vacuum is outside the tube, and the thermocouples were in the insulating vacuum. The thermocouples have a fiberglass backing with an adhesive coating, and they were stuck to tube at the measuring points.

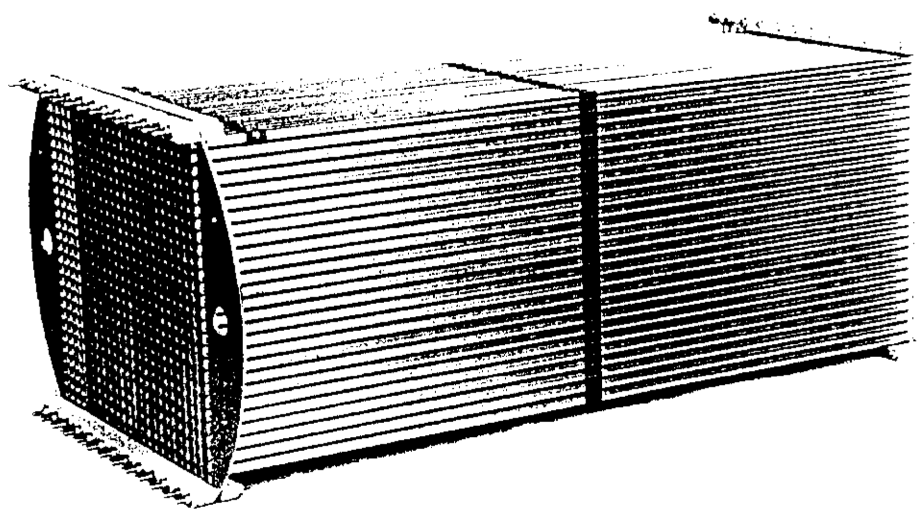

Figure 2. Photograph of the heating element lying on its side during construction.

The measuring points were as follows:

1. On the copper tube below the beginning of the resistive thin wall stainless steel section. This one was used to measure the temperature of the incoming gas.
2. On the stainless tube, 5.08 cm from the bottom.
3. On the stainless tube, 24.05 cm from the bottom.
4. On the stainless tube, 45.46 cm from the bottom.
5. On the attached copper tube, above the stainless section. This one was used to measure the temperature of the heated gas.

The apparatus is equipped with standard capacitance type pressure transmitters and pressure taps with sense lines to the transmitter. Readings are made of the incoming pressure and the pressure drop across the measuring tube. Readings are also made of the current through the tube and the voltage drop.

A special VAX fortran program was written which predicts the temperature distribution in the tube and the temperatures at the sense points. The motivation for the calculation and the test is to compare the results of the program and the input correlations with the results of the measurements.

This program is much more complex than the program used to size the heating tubes because it must account for thermal conduction to make sense out of the temperature readings near the ends of the tube. Conduction near the ends significantly affects the wall temperatures measured. The inputs to the calculation are the incoming gas temperature, the current in the tube, the resistivity function, and the voltage across the tube.

In order to compute the effects of thermal conduction, a set of values for the wall temperatures in each segment is stored in an array. Starting values must be provided, but the result is insensitive to these, and a simple linear variation over the length from the incoming gas temperature to the exit gas temperature works fine. Normally the are 100 segments of the tube used for approximation. The program adds thermal conduction from the adjacent segment or an end. The heat balance in a segment then becomes

$$Q_g = Q_I + Q_c$$

This heat transmitted to the gas is in balance with the heat generated by the electric current and net heat conducted into the segment. This net heat is used to update the enthalpy and temperature and pressure of the gas stream in the step. In this manner, the program steps through the whole tube. After this pass, the results of which depend on the starting array of wall temperatures, all the wall temperatures are improved (iterative) using the current gas temperature and the heat transfer correlation.

The iterations are continued until the wall temperatures stop changing and until the heat computed from the net enthalpy change of the gas agrees with total heat transmitted from the wall computed from the heat transfer coefficient. The procedures converges reliably, but it takes about 2 minutes of computer time to determine a solution for a new run.

Figure 4 shows a summary of the wall temperature measurements. The curves are the results of the computer calculations, and the data points are measurements of wall temperatures, DATN for nitrogen points and DATH for helium points. The curves shown for nitrogen gas and for helium gas are representative and span the range of the data.

In the case of helium, the data and the curves agree well except for the point DATH12 which is at the lowest current, 8 amperes, and the lowest pressure, 0.9 kPa. The nitrogen data seems to have a systematic disagreement which is worst at the lowest pressure, .5 kPa, and current, 6 amperes.

The nitrogen heat transfer coefficients are on the average about 10% too high as predicted by the correlations. This conclusion does not apply

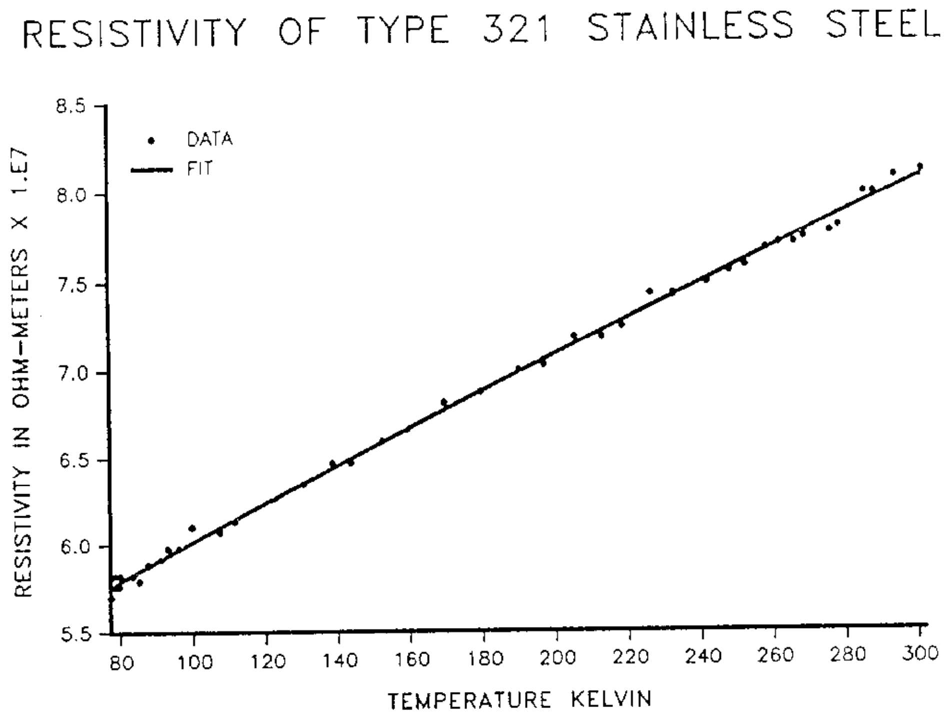

Figure 3. Plot of the resistivity of type 321 SS

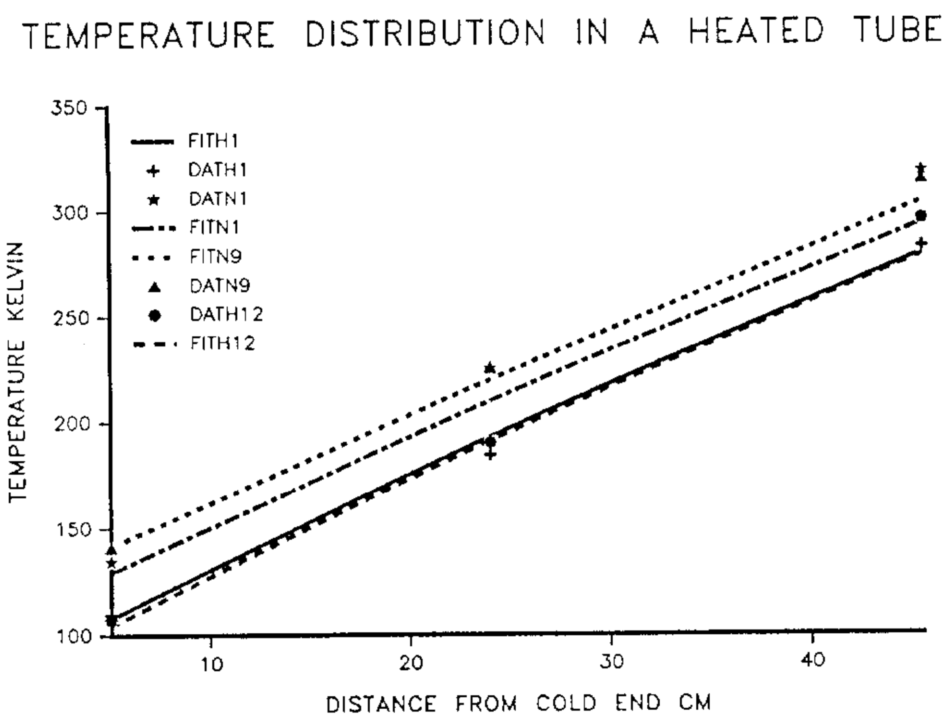

Figure 4. Plot of the wall temperature versus distance from the bottom of the tube

to the very low pressure regime, where the worst error occurs at the lowest density point. This worst error has the heat transfer correlation for h too high by 62%. This could just as well be in the nitrogen properties routines, which could be in error also at the low pressure end. The nitrogen properties came from another routine obtained from Cryodata call GASPAK. Earlier nitrogen routines did not even run below 10.133 kPa (.1 atm)

A possible error in the nitrogen heat exchange or nitrogen properties does not affect the design of the heater element.

The pressure drop results were something of a surprise. The computed pressure drops in the nitrogen run were in very close agreement to the observed pressure drops within errors in the measurements, which were typically 3 %. The helium data on the other hand showed a systematic error in that the computed pressure drops were too small by an average of 5.7 %. Measure measurement error is again typically 3 %. The errors seem to be distributed evenly across the mass flow range and pressure drop range. The pressure drops ranged from .03 kPa to .146 kPa. No explanation is available at this time. The effect is not large enough to cause a major problem in the existing heater element design.

NOTATION

Δp	pressure drop	Pa
ΔL	change in length	m
G	mass velocity	kg/m^2 s
Re	Reynold's number	dimensionless
D	inside pipe diameter	m
Pr	Prandlt's number	dimensionless
k	thermal conductivity	W/m K
h	heat transfer coefficient	W/m^2 K
Q_I	heat generated by electric current in segment	W
ΔT	difference in temerature	K
ρ	gas density	kg/m^3
$\frac{dm}{dt}$	mass flow rate	kg/s
ΔH	change in enthapy	W/kg
Q_g	net heat transferred to gas	W
Q_c	net heat transferred to a wall segment by conduction	W

REFERENCES

1. K. D. Timmerhaus and T. M. Flynn, "Cryogenic process engineering", Plenum Press, New York (1989)
2. S. W. Van Sciver, "Helium cryogenics",Plenum Press, New York (1986)