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Propagation of nitrogen gas in a liquid helium cooled vacuum tube following sudden vacuum loss – Part II: Analysis of the propagation speed

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ABSTRACT

The propagation of near-atmospheric nitrogen gas entering a liquid helium (LHe) cooled vacuum tube following an accidental loss of vacuum will be strongly influenced by condensation of the gas on the tube wall. Our previous experimental study revealed that in presence of condensation, the propagation speed of the gas front decreases nearly exponentially as the front advances in the tube. In the present paper, the exponential decrease is studied semi-analytically. We reduce the analytical model of the front speed, using assumptions, to show its derivative in the direction of propagation to be proportional to the mass deposition rate near the front. The deposition rate is then obtained at discreet locations along the tube from the condensation heat transfer rate at these locations. We find the deposition rate to diminish nearly exponentially along the tube so that the spatial derivative of the speed will show the same effect. In this special case, the front speed will also fall exponentially along the tube. Within the experimental and procedural uncertainty, the exponential decay length-scale of the mass deposition rate also agrees reasonably with the empirically determined exponential decay length-scale of the propagation speed.

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1. Introduction

The beam-line of a superconducting particle accelerator is a long channel holding high vacuum on its inside while being immersed in liquid helium (LHe) [1]. If this beam-line accidentally ruptures at a location exposed to atmospheric air, the air will rapidly flow into the channel and propagate down the vacuum space. The propagation behavior of the air front must be known in order to arrest the front and restrict the beam-line contamination to a minimal length. Past work on this subject has shown the loss-of-vacuum induced air propagation in a beam-line [2] or in a simple LHe cooled tube [3] to be substantially slower than in a vacuum tube at room temperature [4]. By systematically studying propagation of nitrogen gas (a substitute of air) in high vacuum tubes at different wall temperatures, our previous report [5] identified gas condensation to be a must for this slow propagation. Our experiments also brought out an interesting feature that the front, in the presence of condensation, gets slower as it advances along the channel. Additionally, the empirical fits to the measured propagation data showed the front speed along the channel to decrease nearly exponentially. An analytical model formulated for the front propagation speed explained why the speed decreases along the tube, but did not provide any insight as to why this decrease is exponential.

The analyses presented in this paper provide further support to the previously observed exponential fall in the propagation speed. We reduce the analytical expression of the propagation speed to a form that can be compared directly with the empirical fits to our experimental data. The parameters required to work with this form are determined from the calculated rates of condensation heat transfer and mass deposition on the tube. The result of this procedure shows that the propagation speed given by the analytical model also falls off exponentially along the tube with nearly the same exponential decay length-scale as that of the empirical fit.

2. Experimental setup and procedure

Elaborate details of the experimental setup and the experimental procedure are given in [6]. Fig. 1 depicts the general characteristics of the experimental setup. In this setup, a copper tube (1.5 m long, 38 mm outer diameter, and 3 mm wall thickness) evacuated to $\approx 10^{-4}$ Pa is immersed in a large bath of LHe at 4.2 K. The tube vacuum is isolated from a tank containing nitrogen gas by means of a fast-opening solenoid valve (SV). On opening this valve the

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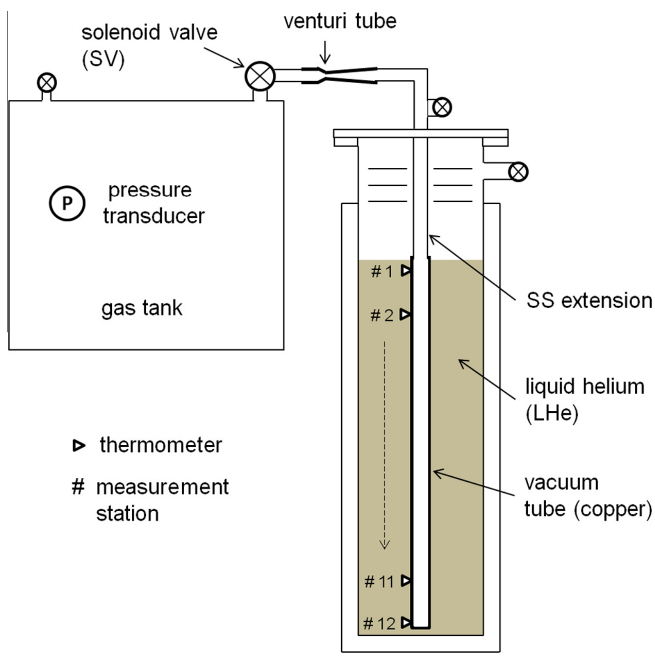

Fig. 1. Schematic of the experimental setup used for studying the propagation of nitrogen gas in a LHe cooled vacuum tube.

room-temperature nitrogen gas in the tank flows rapidly into the tube, propagates down the vacuum space, and condenses on the inner surface of the cold tube. The tube carries on its outer surface twelve thermometers equally spaced by 0.125 m along the length (except the last pair, which has 0.25 m spacing). These thermometers measure the rise in the tube temperature resulting from the condensation of the warm gas on the cold tube. The condensation heat and mass transfer calculations presented further in this paper essentially use the same temperature data that were previously used in determining the front propagation speed [5]. We recall here also from [5] that these temperature data have been obtained from three separate experiments that started with 50 kPa, 100 kPa, and 150 kPa nitrogen gas in the supply tank. In this paper we have in general referred to the experiments as '50 kPa experiment', '100 kPa experiment', and '150 kPa experiment' according to the tank pressure at which that experiment started.

3. Analytical modeling

3.1. Previous observations and modeling [5]

The principal observation from our propagation measurements is that the front speed decreases along the vacuum tube. This deceleration is consistent among the 50 kPa, 100 kPa, and 150 kPa experiments, which essentially had the gas vented to the vacuum tube at different mass-flow rates. Furthermore on regression analysis, the front propagation speed in the vacuum tube is seen to follow an exponential decay relation of the form:

$$v|_x = (b/a)e^{-x/b} \tag{1}$$

In this expression $v|_x$ is the front speed when the front is located at x in the tube (the tube entrance is at $x = 0$), while a and b are parameters of the empirical fit to the measured propagation data. These parameters for the three experiments are summarized in Table 1.

We also formulated an analytical expression for the front propagation speed by applying conservation of mass to the scenario depicted in Fig. 2. In the illustration of Fig. 2, the gas at an in-flow rate $\dot{m}_{in}$ enters a cold vacuum tube of inner diameter

Table 1
Parameters a and b appearing in $v|_x = (b/a)e^{-x/b}$ with their standard errors [5].

p_{start} [kPa]	a [s]	b [m]
50	0.041 ± 0.005	0.46 ± 0.02
100	0.031 ± 0.005	0.63 ± 0.04
150	0.035 ± 0.010	0.95 ± 0.15

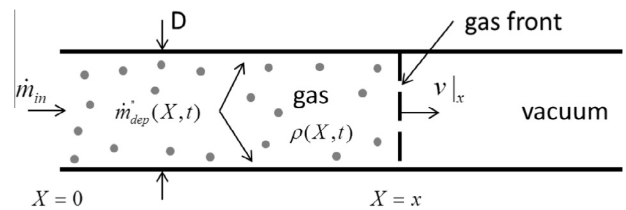

Fig. 2. Propagation of a condensable gas in a vacuum tube.

D from location $X = 0$, and a gas front propagates along the x direction. The local gas density is ρ and the local rate of mass deposition (condensation) per unit area on the inner surface of the tube is $\dot{m}''_{dep}$. For this scenario the front speed when the front is located at $X = x$ is given by (conditions at the front are denoted by $|_x$):

$$v|_x = \frac{\dot{m}_{in} - \pi D \int_0^x \dot{m}''_{dep}(X)dX}{\pi D^2 \rho|_x/4} \tag{2}$$

As elaborated in [5], Eq. (2) accounts for the observed decrease in the propagation speed with increasing travel length x. We now further work with this model to show that the decrease with the travel length is nearly exponential as our experimental data have pointed out.

3.2. Extension of the analytical model

Differentiating with x, the empirical relation $v|_x = (b/a)e^{-x/b}$ leads to:

$$(dv/dx)|_x = (-1/a)e^{-x/b} \tag{3}$$

which implies that the spatial derivative of the front speed should also decay exponentially along the tube. Similarly, Eq. (2) on differentiation with x gives:

$$(dv/dx)|_x = \frac{-4\dot{m}''_{dep}|_x}{D\rho|_x} \tag{4}$$

In this derivation, we have assumed that the gas density at the front does not vary significantly along the tube so that $(d\rho/dX)|_x \approx 0$. If conditions given by Eqs. (3) and (4) are equivalent, then it follows that the rate of mass deposition at the front $\dot{m}''_{dep}|_x$ should decrease exponentially as the front advances along x and should have the same exponential decay length-scale, b as in Eq. (3). The mass deposition rate at the front when the front is located at x should then take the form:

$$\dot{m}''_{dep}|_x \propto e^{-x/b} \tag{5}$$

In our previous report, we discussed some inherent difficulties that do not allow calculating the front speed from its analytical form (Eq. (2)). The main difficulty is quantifying the mass deposition rate over the extent of condensation, *i.e.*, from $X = 0$ to $X = x$ so as to evaluate the integral term in Eq. (2). The procedure described above essentially circumvents this difficulty by removing this integral and working only with the mass deposition rate at the front. The local mass deposition rate can be obtained as

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