International Journal of Heat and Mass Transfer 96 (2016) 573–581

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Propagation of nitrogen gas in a liquid helium cooled vacuum tube following sudden vacuum loss – Part I: Experimental investigations and analytical modeling

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ARTICLE INFO

Article history:
Received 27 July 2015
Received in revised form 24 January 2016
Accepted 30 January 2016
Available online 11 February 2016

Keywords:
Accidental vacuum loss
Propagation speed
Superconducting
Particle accelerator
Beam-line

ABSTRACT

This paper describes propagation of near atmospheric nitrogen gas that rushes into a liquid helium (LHe) cooled vacuum tube after the tube suddenly loses vacuum. The loss-of-vacuum scenario resembles accidental venting of atmospheric air to the beam-line of a superconducting particle accelerator and is investigated to understand how the in-flowing air will propagate in such geometry. In controlled experiments, we simulated loss of vacuum by rapidly venting a large reservoir of nitrogen gas (a substitute for air) to a vacuum tube immersed in a LHe bath at 4.2 K. The resulting rise in the tube pressure and temperature were measured by pressure probes and thermometers arranged along the tube length. The data show that the propagation of nitrogen gas in the LHe cooled vacuum tube is orders of magnitude slower than in the same tube at room temperature. Interestingly, the gas front speed in the LHe cooled tube also decreases along the tube. A gas propagation model developed by employing conservation of mass identifies mass transfer (gas condensation in the tube) as the principal cause of the slow propagation as well as of the front deceleration. Some limitations of this analytical model are discussed in the context of quantifying the propagation speed. The speed obtained from direct measurements is seen to decrease exponentially along the tube. This exponential decay form of the propagation speed well represents the data from experiments that have different mass flow rates of nitrogen gas flowing into the vacuum tube after venting.

1. Introduction

When a long channel holding vacuum at room temperature is abruptly opened to atmosphere, the in-flowing air will cause a pressure front to propagate down the channel. The front speed in this scenario can be measured by means of an array of pressure probes placed in the channel [1]. The theoretical maximum speed of a gas propagating in a perfect vacuum, called as 'escape speed', is given by $2a/(\gamma - 1)$ [2]. In this expression, a is the speed of sound in the gas at its source and γ is the ratio of specific heats. For air at room temperature, the escape speed is nearly 1700 m/s. This theory, however, assumes perfect vacuum in the channel and that the density of the gas front adjacent to the vacuum is zero. Due to this vanishing density, no pressure measurement apparatus with a finite measurement resolution can record the theoretical speed of the front. Nonetheless, in realistic experiments such as by Takiya [3] the front speed in a vacuum channel (pressure $\approx 10^{-3}$ Pa) was recorded to be as high as 700 m/s. Although substantially lower than the theoretical maximum, this speed is still nearly twice the speed of sound in air at room temperature.

The beam-line of a superconducting particle accelerator (European Spallation Source for example) is a special case of a high vacuum channel (pressure $\approx 10^{-8}$ Pa), which is cooled by immersion in liquid helium (LHe) [4]. When such a channel suddenly loses its vacuum to atmospheric air, the air front is observed to propagate at speeds substantially lower than in vacuum channels at room temperature. Past research [5,6] that investigated vacuum loss in LHe cooled channels has reported this speed to be of the order of 10 m/s. This order of magnitude reduction in the propagation speed is believed to be due to the intensive mass and heat transfer from the in-flowing warm air (≈295 K) to the extremely cold walls of the channel (4.2 K or colder). In this paper we present experimental and analytical findings that elucidate the role of this heat and mass transfer in slowing the propagation of nitrogen gas (a substitute of air) in a LHe cooled channel. An experimental

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.01.077
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apparatus [7] has been devised to simulate a sudden loss of vacuum in a 4.2 K LHe cooled tube and to measure the resulting rise in temperature and pressure along the tube as the gas propagates. The influence of mass and heat transfer on the propagation is investigated experimentally. We explain some characteristics of gas propagation with an analytical model formulated using conservation of mass. Some limitations in evaluating the propagation speed using the model are described and then the propagation speed is obtained directly from the measured data. Our analysis and experiments provide first insights into the nature of the loss-of-vacuum induced air propagation in a LHe cooled vacuum channel.

2. Experimental setup and procedure

Fig. 1 shows the general characteristics of the experimental apparatus. The propagation measurement site is a vacuum tube (OFHC copper, length 1.5 m, inner diameter 32 mm, and wall thickness 3 mm) immersed in a bath of LHe at its normal boiling temperature of 4.2 K. Accidental loss of vacuum is simulated by opening the solenoid valve (SV) (~25 ms opening time), which vents a tank (85 liters in volume) containing nitrogen gas to the cold vacuum tube. The tube is equipped with an array of miniature pressure probes on the inside and thermometers embedded in the tube wall from the outside. These sensors record the arrival times of the gas front at sequential locations along the tube. The gas propagation speed is deduced from the separation between the sensors and the measured arrival times. The gas flowing from the supply tank to the vacuum tube is made to choke using a venturi tube so as to generate a near constant mass flow into the vacuum tube. Note that although the venturi chokes after opening the SV, the mass in-flow rate gradually decreases as the tank depressurizes with time. However, this decrease is small so that simple time averaging provides a reasonable estimate for the near-constant mass in-flow rate. The mass in-flow rate is determined from the tank de-pressurization rate recorded by a pressure transducer placed inside the gas tank. The mass in-flow rate calculation and averaging are elaborated in Appendix A. A variety of mass flow rates can be obtained from this configuration by starting with different pressures of the gas in the supply tank.

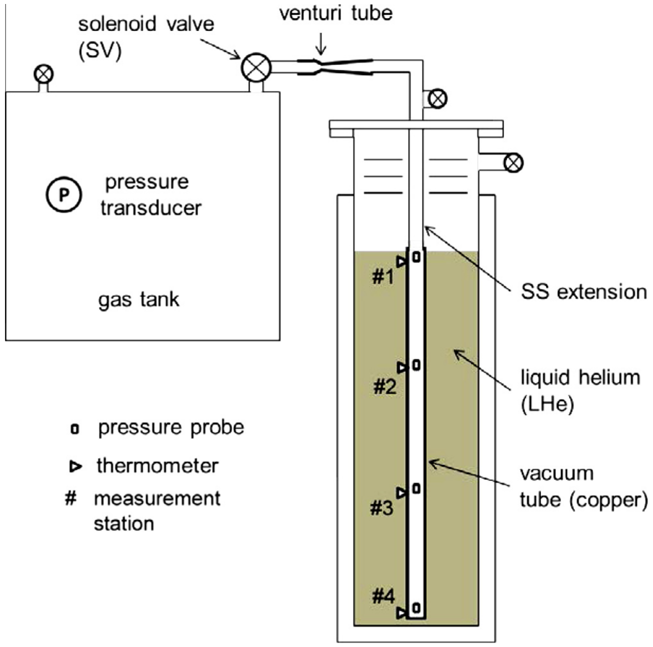

Fig. 1. Schematic of the propagation measurement setup.

The installation techniques for the pressure probes and the thermometers to ensure their proper operation in the cryogenic environment have been elaborated in [7]. The pressure sensors are Kulite XCQ-092 probes with 0-100/150 kPa range of operation. All pressure probes were calibrated using MKS 626-Baratron capacitance manometer as a reference. During experiments, the pressure probes were excited at 10 VDC using TENMA 72-7245 voltage supply and the probe output voltages were measured on National Instruments USB-6225 DAQ at a sampling rate of 20 kHz per probe. The uncertainty in pressure measurement is ±20 Pa in the entire operating range and is dominated by electromagnetic interference (noise). Lake Shore Cernox® 1050 SD thermometers measured the tube temperature. These RTDs were calibrated in the temperature range of 2-80 K referenced to a factory calibrated thermometer. During experiments a 3 μA constant current source (in-house design) powered the thermometers while the voltage drop was recorded by Data Translation DT-9824 DAQs at 4.8 kHz per sensor. Temperature measurement uncertainty is typically ±20 mK in the 2-20 K range and ±0.2 K above 20 K. All DAQ boards are time-referenced to the voltage trigger that opens the solenoid valve. This trigger also provides the 'zero time' for all the measurements.

3. Results and discussion

We first present and discuss the results from the loss-of-vacuum experiments that started with the vacuum tube at three different temperatures – 295 K, 77 K, and 4.2 K. By introducing an increasing temperature difference between the gas flowing in (at room temperature) and the tube wall, these experiments signify the effect of the heat and mass transfer on the gas propagation speed. The gas front propagation in the LHe cooled tube is then described in terms of the pressure and temperature data recorded during the 4.2 K experiment. The propagation speed is determined by analyzing these data in a later section of this paper.

3.1. Effect of heat and mass transfer on propagation speed

Separate experiments with the vacuum tube at 295 K, 77 K, and 4.2 K bring out the effect of the heat and mass transfer from the gas to the tube, on the gas propagation speed. Each experiment started with 100 kPa, 295 K nitrogen gas (99.999% pure) in the supply tank while the tube was evacuated to $\approx 10^{-4}$ Pa. Fig. 2(a) shows the propagation captured by the four pressure probes, with 0.5 m spacing, during an experiment with the tube at room temperature (RT $\approx$ 295 K; the experiment referred to as 'run-RT'). Travel time of $\approx$2.5 ms over 1.5 m (first and fourth probe) gives an average propagation speed of $\approx$600 m/s. In another experiment the vacuum tube was immersed in liquid nitrogen, which holds the tube wall at 77 K (run-LN2). In Fig. 2(b), the pressure traces from run-LN2 also show the speed to be $\approx$600 m/s. Next, the evacuated tube was cooled by liquid helium at 4.2 K (run-LHe). The pressure traces after the loss of vacuum in this experiment (Fig. 2(c)) show drastic reduction in the propagation speed. A travel time of $\approx$450 ms over 1.5 m translates to an average propagation speed of $\approx$3.3 m/s.

In run-RT the tube wall at 295 K cannot condense nitrogen gas. Assuming the dynamics of expansion does not produce a large drop in the gas temperature, the convective heat exchange between the gas ($\approx$295 K) and the 295 K tube is expected to be low. In run-LN2 convective heat exchange between the gas and the 77 K tube will be greater than that in run-RT. Condensation is still not possible because the pressure in the tube (<0.5 kPa) for the duration of propagation (0–3 ms) is much less than 100 kPa – the saturation vapor pressure of nitrogen at 77 K. Nitrogen gas pressure must be at least 100 kPa for the gas to condense on a 77 K surface. Very similar propagation speeds in run-RT and run-LN2 suggest that