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Thermal conductivity of subcooled liquid oxygen

D. Celik [a,*], S.W. Van Sciver [a,b]

[a] *National High Magnetic Field Laboratory, Florida State University, 1800 E Paul Dirac Drive, Tallahassee, FL 32310, United States*
[b] *Mechanical Engineering Department, FAMU-FSU College of Engineering, Tallahassee, FL 32310, United States*

Abstract

The thermal conductivity of liquid oxygen below 80 K and pressures up to 1 MPa has been measured using a horizontal, guarded, flat-plate calorimeter. The working equation of the calorimeter is based on the one-dimensional Fourier's law. The gap between the calorimeter plates was measured in situ from a capacitance measurement. The cooling power to the calorimeter is provided by a two-stage Gifford–McMahan cryocooler. The absolute temperatures are measured using platinum resistance thermometers. The results are compared to existing data and analytical models.
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1. Introduction

Liquid oxygen is the oxidizer for spacecraft engines. It is also used to provide breathing air to the astronauts. The liquid form is also more suitable for storing large quantities for industrial applications, which includes but is not limited to steel blast furnaces, glass making industry and a number of chemical processes.

The transport and thermodynamic properties of liquid oxygen have been studied extensively. However, available thermal conductivity data, which are needed when calculating heat transport processes such as temperature distribution in storage vessels, are very limited below about 77 K and non-existent below the freezing point of nitrogen [1–3]. In this paper, we report the thermal conductivity measurement results on subcooled liquid oxygen between 55 and 81 K at pressures up to 1 MPa. The results are compared with the available

experimental data in the literature and analytical models developed at NIST [4].

2. Description of the experimental apparatus

The apparatus used in these measurements is described in Ref. [5]. However, some modifications have been made since that article was published and, from the point of completeness, we describe the modified apparatus in detail in the following paragraphs.

The design of the apparatus is based on the guarded, horizontal flat-plate calorimeter [6]; however, we have made two major modifications from the original apparatus in order to eliminate the adjustments to account for the thermal conduction in the calorimeter material and to eliminate the effect of the pressure on the gap between the calorimeter plates. In order to eliminate the adjustment due to the thermal conduction in plate material, we have placed the thermometers directly under the surfaces that are in contact with the liquid. The distance between the center of the thermometers and the plate surfaces are less than 1.7 mm. Combined with the high

thermal conductivity of copper used for the calorimeter plates, this short distance keeps the required adjustment to the temperature reading due to the conduction in the plate material below 0.001% in the temperature range of the experiments. The effect of pressure on the gap between the plates is eliminated by inserting a separate plate rather than using the cell body as the cold plate. The addition of this separate plate also allows us to use a capacitance meter to measure the gap accurately.

The schematic of the calorimeter is given in Fig. 1. A hot plate is formed by sandwiching a film heater with a 100 Ω resistance between two 76.6 mm diameter copper discs with a thickness of 6.4 mm. Discs are bolted together using #0–80 stainless steel screws. This construction, however, caused a temperature difference between the upper and the lower parts of the hot plate when the heater is energized, as discussed in the next section. A platinum resistance thermometer [7] is inserted in each disk through 2.0 mm diameter radial holes that extends from the side to about 4 mm beyond the center. The center of the radial hole is 1.7 mm below the surface of the discs that is in contact with the liquid.

The hot plate is attached to the first thermal guard, which is attached to the second thermal guard each using three 2-mm-diameter G-10 supports and secured with epoxy. The assembly process is done on a thick glass surface to ensure that the components are on the same plane. Both guards are made of copper and the inner diameter of the first guard is 80.0 mm. In addition to a film heater that is sandwiched between the guard body and a copper disc, each guard has a wire heater wrapped around the body. The first thermal guard has two platinum resistance thermometers: one at the center of the top, inserted similar to the hot plate thermometers and the second one is on the side of the guard, which was utilized to verify a uniform temperature distribution in the guard. The second thermal guard has only one platinum resistance thermometer at the center of the top. This whole assembly is supported by three pieces of silica glass on the copper cold plate. The cold pl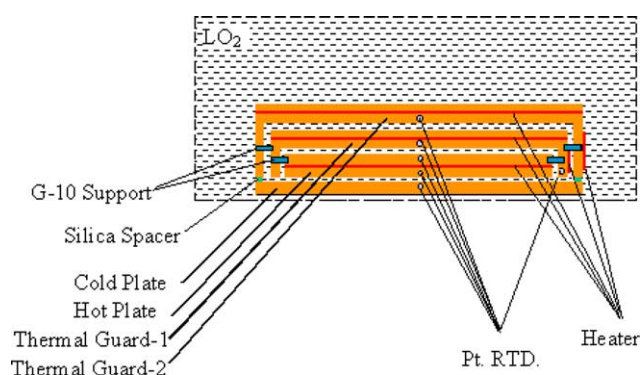ate is placed at the bottom of the measurement cell and electrically insulated from it by means of a piece of Kapton® tape for the capacitance measurement, as explained in the next section. The cold plate has a platinum resistance thermometer installed similar to those in the hot plate.

The thermometer and heaters are installed using Apiezon-H [7] grease to ensure good thermal contact. The thermometer lead wires are wrapped around their respective parts to minimize heat conduction along the length. All the lead wires are formed from twisted pairs to minimize the electronic noise. The hot plate assembly and the cold plate are placed inside the measurement cell, made of Glidcop® Al-25 [8]. The cooling power is provided by a two-stage model GB-37 Gifford–McMahan cryocooler by Cryomech [9]. Compared to other cryogens as the cooling source, the addition of the cryocooler enables a very broad temperature range for the experiments. The temperature of the cell is controlled with a temperature controller, which utilizes a silicon diode temperature sensor in the feedback loop to control the power input to a film heater installed on the thermal link between the cryocooler stage and the measurement cell, see Fig. 2.

Gaseous oxygen is condensed inside the cell and pressurized up to 1 MPa using helium gas during the measurements. The solubility of helium in liquid oxygen is very small, less than 0.04 mol% in the range of the experiments [10]. The purity of the gases used for the measurements is 99.996% and contain the following [11]: water < 1 ppm, methane < 0.5 ppm, carbon monoxide < 1 ppm, carbon dioxide < 1 ppm, argon < 20 ppm, and nitrogen < 10 ppm. A cold trap at 77 K is utilized to minimize the impurities; however, some trace
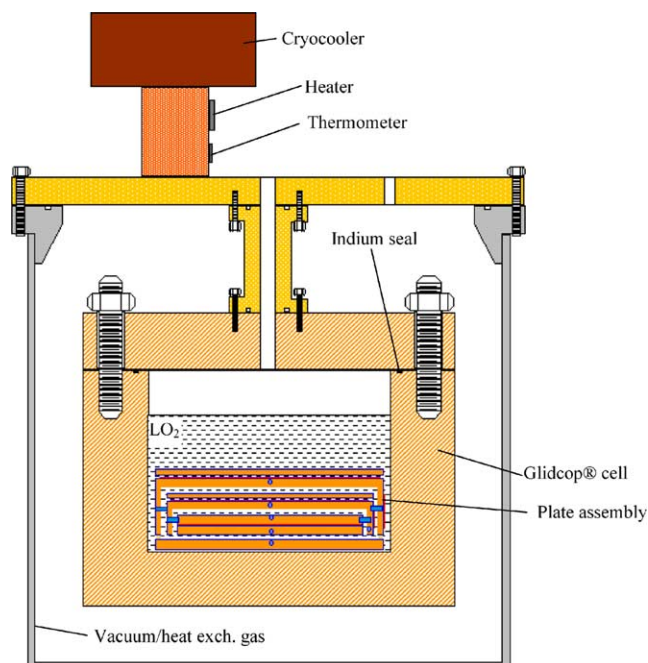

Fig. 1. The schematic of the guarded, flat-plate calorimeter.

Fig. 2. The schematic of the experimental cell.