AIP | Review of Scientific Instruments

Note: A passively cooled heat pipe for spectroscopy

J. Gillot, C. Lemarchand, I. Braud, B. Decamps, A. Gauguet, J. Vigué, and M. Büchner

Citation: Review of Scientific Instruments **84**, 106109 (2013); doi: 10.1063/1.4826083
View online: http://dx.doi.org/10.1063/1.4826083
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/84/10?ver=pdfcov
Published by the AIP Publishing

Note: A passively cooled heat pipe for spectroscopy

J. Gillot, C. Lemarchand, I. Braud, B. Decamps, A. Gauguet, J. Vigué, and M. Büchner[a)]
Laboratoire Collisions Agrégats Réactivité -IRSAMC, Université de Toulouse-UPS and CNRS UMR 5589, 118, Route de Narbonne, 31062 Toulouse Cedex, France

(Received 30 May 2013; accepted 4 October 2013; published online 21 October 2013)

We have developed and characterized a heat pipe for lithium spectroscopy, which is cooled only by air-convection, although its operating temperature is 330 °C: its construction is simple, of moderate cost and it is very reliable. A thermal model proves that heat-pipes without water cooling can be used up to considerably higher temperatures. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4826083]

Heat pipes were initially developed as heat conduction devices.[1,2] In 1969, Vidal and Cooper applied heat pipes to spectroscopic studies:[3] it is thus possible to produce an atomic or molecular vapor in the central part of a heated tube terminated by water-cooled windows which are protected against vapor condensation or chemical attack by an inert buffer gas. The vapor condenses on a mesh placed in the pipe and capillary forces transport the liquid back to the evaporation zone. Many spectroscopic heat pipes have been built following this design[4] and a complete review exceeds the scope of this note. Their popularity is proved by efforts of cost minimization[5] and by their use in education.[6]

When a laser must be locked on a lithium transition, a lithium heat pipe is the most common choice,[7–11] because glass cells suffer from chemical attacks at the temperatures needed to reach a sufficient vapor pressure. Another method is to lock an auxiliary laser on a molecular iodine transition lying close to the lithium D lines and to measure the frequency beat with the laser resonant with lithium. Molecular iodine offers a large manifold of transitions in the 500–700 nm range[12] and, usually, a favorable transition can be found close to the required laser frequency: for instance, Huang *et al.*[13,14] used an iodine line at about 6 GHz of the D_1-line of ^{7}Li and they achieved a high frequency stability of the laser locked on the iodine line.

Heat pipe windows are traditionally water-cooled, with the risk of water leaks on an optical table covered by many expensive components. We describe here a lithium heat pipe operating at $T_{HP} = 330\,^\circ$C, cooled only by air convection. We present a saturated absorption spectrum of lithium D_2-line recorded with this heat pipe. Finally, we describe a simple thermal model which explains where heat is dissipated and which can be used to extrapolate this design to higher temperatures.

Fig. 1 shows a technical drawing of our heat pipe, which is built with common UHV components: DN35CF stainless steel flanges are soldered on a stainless steel tube (external diameter $d = 38$ mm, wall thickness $e = 1.5$ mm). The flanges are sealed by DN35CF glass windows with copper gaskets. Its overall length is 330 mm. The 110 mm-long central part is heated by a 2.5 m-long 2 mm-external diameter, thermocoax heating element, with two oppositely wound layers, in order to minimize the magnetic field. The mesh, placed inside the middle part of the tube, is a 200 mm long sheet cut in a stainless steel wire grid with a 90 μm period.

After a thorough cleaning of the pipe and of the mesh, we introduce about 1 g of pellets of natural lithium on the mesh and we evacuate the heat pipe by a turbomolecular pump connected through the 4 mm internal diameter stainless steel tube (see Fig. 1). We then introduce argon as a buffer gas at a pressure near 0.2 mbar and we close the valve (HOKE model 7155). During the first operation, a temperature near 400 °C is needed to break the oxidized shells of the pellets. The usual operating temperature, $T_{HP} = 330\,^\circ$C, is reached with a power $P = 60$ W ($I = 3$ A and $V = 20$ V). At this temperature, lithium vapor pressure and density are $p \approx 10^{-5}$ mbar and $n \approx 10^{11}$ atoms/cm^3.[16] With a room temperature $T_0 \approx 24\,^\circ$C, we measured the windows temperature to be near 31 °C. With the help of a diffusion model,[15] we estimate the thickness of the lithium layer deposited on the windows to be of the order of 2 nm/year, which is negligible.

We use our heat-pipe in a traditional saturation spectroscopy set-up to frequency lock lasers on one lithium transition. A linearly polarized and phase modulated laser beam (Toptica DL100, pump beam with a waist $w_0 = 3$ mm, 1 mW power, modulation frequency about 5 MHz), is sent through the heat pipe, pass through a density filter, a quarter-wave plate and is reflected by a mirror. The attenuated outgoing beam (probe beam), which is orthogonally polarized with respect to the incoming pump beam, is reflected by a polarization cube and sent to a photodiode. After demodulating the electrical signal, we obtain the derivative of the saturated absorption spectrum, which is used as an error signal and we obtain a laser frequency jitter less than 0.5 MHz.

Fig. 2 shows a typical spectrum of the D_2 line of ^{7}Li ($^2S_{1/2}$, $F = 1, 2 \rightarrow {}^2P_{3/2}$, $F' = 0, 1, 2, 3$) at $\lambda_L = 671$ nm, with a Doppler-generated level crossing, clearly visible in the middle of the two main lines. On the FM spectroscopy, the peak-to-peak frequency is 18 MHz comparable to the hyperfine splitting of the $^2P_{3/2}$ state (18.3 MHz[17]). We have also observed the D_1 line of ^{7}Li and D_2 line of ^{6}Li. For the D_1 line of ^{7}Li, the hyperfine transitions are well resolved and the lines can be well fitted by the derivative of a Lorentz profile, with a

a)Electronic mail: matthias.buchner@irsamc.ups-tlse.fr

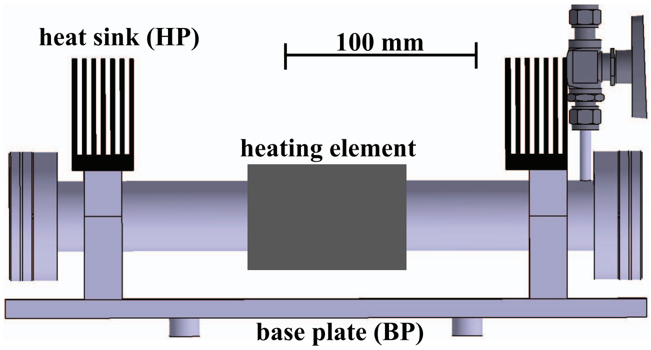

FIG. 1. Scale drawing of our heat-pipe and its support. The heat is conducted by two thick holders to three heat sinks, the base plate and two electronics heat sinks. The base plate area is about 460 cm^2 and each finned heat sink has a total area close to 400 cm^2.

measured Lorentz width equal to 29 MHz. The Lorentz width of each hyperfine components should be equal to $\Gamma/2\pi = 5.9$ MHz but there are several sources of line broadening: laser saturation, with a maximum power density of 3.5 mW/cm^2 and a saturation intensity 2.6 mW/cm^2,[18] broadens the line width to 9 MHz; Zeeman effect due to the local Earth field contributes for about 1.5 MHz and the magnetic field due to the heating element has a negligible effect; finally collision broadening by argon gas[19] should induce an additional broadening near 3 MHz. We think that the dominant contribution to the observed line width is collision broadening by gases produced by outgassing of the heat pipe walls. Typical broadening rates being 10−20 MHz/mbar, a pressure of about 1 mbar is sufficient to explain the observed width.

We have estimated the various heat fluxes, by describing the system as a network of thermal resistances connecting the heat source at temperature T_{HP} to the heat sinks which are the surrounding air and the optical table, both at room temperature T_0. We must consider heat transfer by conduction and by air convection. As the heat pipe is symmetric, the network represents only one half of it (see Fig. 3). In the case of conduction, we approximate the thermal resistance R of the different elements by the equation $R = L/(\kappa S)$, which is valid for a bar of length L, section area S (when the shape is not a bar,

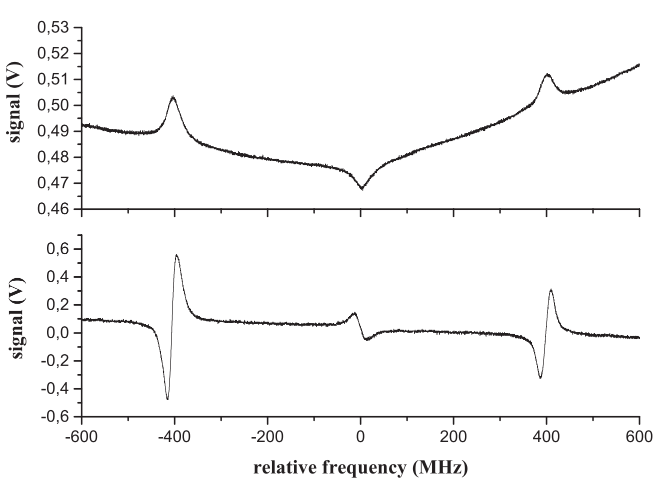

FIG. 2. (Upper panel) Doppler-free saturated absorption signal of lithium D_2 lines. The lower panel shows its derivative. The total scan time is 20 ms.

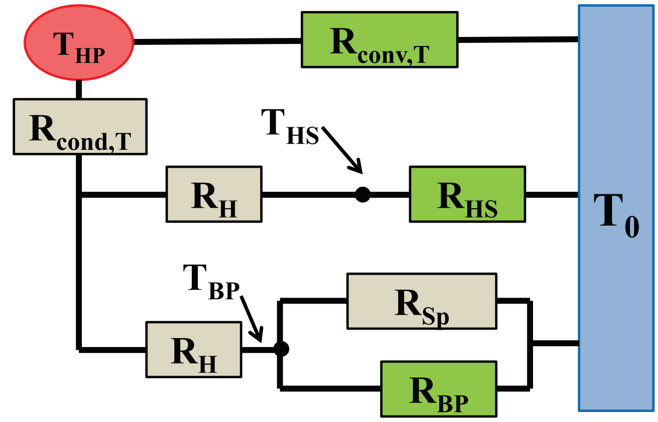

FIG. 3. The network of thermal resistances representing the heat flux of one half of our heat pipe (in grey, conduction resistances and in green convection resistance). The values used in our model are given in Table I. T_{HP}, T_{HS}, and T_{BP} are the temperatures of the heat pipe, of the heat sink, and of the base plate, respectively.

we use approximate values of L and S). The thermal conductivity κ is taken equal to $\kappa_{ss} \approx 16$ W/(K m) for stainless steel and $\kappa_{al} \approx 134$ W/(K m) for aluminium alloy.[20]

Heat dissipation by convection is proportional to the temperature difference and to the area S_{ext} of the external surface. The thermal resistance is given by $R_{conv} = 1/(h_{conv} S_{ext})$. The value of the coefficient h_{conv} depends on the geometry and on the air motion, with values ranging from $h_{conv} = 5$ to 25 W/(K m^2).[21] We neglect the temperature gradients in the base plate and in the electronics heat sinks, because of their high thermal conductivity. For the heat pipe, if we assume a linear temperature gradient, the thermal resistance is given by $R_{conv,T} = 1/(2h_{conv} S_{ext})$ and the validity of this approximation is discussed in the supplementary material.[15]

The total thermal resistance, which determines the heating power, depends on the coefficient h_{conv} which is not well known and we have chosen $h_{conv} \approx 15$ K/(W m^2) to match the total thermal resistance (see Table I for the used thermal resistances). The calculated temperatures of the upper heat sink, $T_{HS} = 49\,°$C and of the base plate $T_{BP} = 37\,°$C, are in reasonable agreement with their measured values $T_{HS} = 43\,°$C and $T_{BP} = 36\,°$C. We have not tried to extend our model to predict the window temperature because of the complexity of the flange assembly. Our model tells us where the power is dissipated: 88% by air convection (53% directly from the tube, 28% through the electronics heat sinks, 7% through the base plate), and 12% by transfer to the optical table, a fraction which can be easily reduced by using low-conduction spacers.

It may be very interesting to reduce the heating power for the same heat pipe temperature or to reach higher temperatures with a similar power. The simplest way is to reduce the pipe diameter because $R_{cond,\,T}$ and $R_{conv,T}$, which dominate the equivalent resistance of the network are both

TABLE I. Thermal resistances in K/W used in our model.

Resistance	$R_{cond,\,T}$	$R_{conv,T}$	R_H	R_{Sp}	R_{BP}	R_{HS}
K/W	21	20	0.14	0.9	3	1.8

inversely proportional to this diameter: for instance, with a 16 mm-external diameter tube having the same 1.5 mm-wall thickness (a pipe commonly used with DN16CF flanges), the heating power will be reduced by a factor 2.4. Another possibility is to use a longer thermally insulated pipe: insulation will reduce the power lost by air convection from the tube and a longer tube will reduce the power transferred to the holders, in order to keep their temperature rather low. By combining these possibilities, with a power below 100 W, it is possible to reach a temperature $T_{HP} \approx 800\,^{\circ}$C, sufficient to work with magnesium or barium.

In this paper, we have described a lithium heat pipe operating at a temperature $T_{HP} = 330\,^{\circ}$C, sufficient for atomic spectroscopy of lithium, as illustrated by a saturated absorption spectrum of ^{7}Li D_2 line. This heat pipe is cooled solely by air convection, which prevents the risk of water leaks on an optical table and which also saves water. The construction of this heat pipe is simple and of moderate cost. The thermal model we have developed tells us the fraction of the heating power transferred to the optical table. This model can be used to extrapolate this design for an operation at higher temperatures and, after design optimization, a temperature $T_{HP} \approx 800\,^{\circ}$C is feasible with a heating power near 100 W, still without water cooling. We have also developed a model to describe lithium diffusion toward the windows and we find that, in agreement with experiment, the thickness of the lithium layer deposited on the windows is negligible.

We thank D. Castex, M. Gianesin, and L. Polizzi for the construction of this heat-pipe and A. D. Cronin for stimulating discussions. We thank CNRS INP, ANR (Grant No. ANR-11-BS04-016-01 HIPATI), and Région Midi-Pyrénées for support.

[1] G. M. Grover, T. P. Cotter, and G. F. Erickson, J. Appl. Phys. **35**, 1990 (1964).
[2] I. C. Finlay and D. B. Green, J. Phys. E **9**, 1026 (1976).
[3] C. R. Vidal and J. Cooper, J. Appl. Phys. **40**, 3370 (1969).
[4] C. R. Vidal, *Atomic, Molecular and Optical Physics, Atoms and Molecules*, Experimental Methods in the Physical Sciences Vol. 29B, edited by F. B. Dunning and R. Hulet (Academic, New York, 1996), pp. 67–83.
[5] D. Hite *et al.*, Am. J. Phys. **65**, 1017 (1997).
[6] T. T. Grove *et al.*, Eur. J. Phys. **30**, 1229 (2009).
[7] K. Ladouceur *et al.*, JOSA B **26**, 210 (2009).
[8] G. Ferrari, Ph.D. thesis, University Paris 6, 2000, see http://tel.archives-ouvertes.fr.
[9] T. G. Tiecke, Ph.D. thesis, University of Amsterdam, 2009 (unpublished), see http://staff.science.uva.nl/.
[10] P. M. Duarte, Ph.D. thesis, Rice University, Houston, 2012 (unpublished), see http://scholarship.rice.edu/handle/1911/70234.
[11] J. Gillot *et al.*, "Optical pumping of a lithium atomic beam for atom interferometry," Eur. J. Phys. (submitted).
[12] S. Gerstenkorn and P. Luc, Atlas du spectre d'absorption de la molécule de l'iode 14800 cm^{-1}–20000 cm^{-1}, Laboratoire Aimé Cotton CNRS II, 1978.
[13] Y.-C. Huang, H.-C. Chen, S.-E. Chen, J.-T. Shy, and L.-B. Wang, Appl. Opt. **52**, 1448 (2013).
[14] Y.-C. Huang, W.-J. Luo, Y.-T. Kuo, and L.-B. Wang, J. Phys. B **46**, 075004 (2013).
[15] See supplementary material at http://dx.doi.org/10.1063/1.4826083 for a description of the lithium diffusion toward the windows and of the thermal equilibrium of a pipe in the presence of conduction and convection.
[16] G. Gundlach *et al.*, Chem. Phys. **124**, 131 (1988).
[17] L. Windholz, H. Jäger, M. Musso, and G. Zerza, Z. Phys. D **16**, 41 (1990).
[18] H. J. Metcalf and P. Van der Straten, *Laser Cooling and Trapping* (Springer-Verlag, New York, 1999).
[19] A. Gallagher, Phys. Rev. A **12**, 133 (1975).
[20] See www.thyssenfrance.com for Aluminium alloy 2017A; See www.goodfellow.com. for stainless steel AISI-304.
[21] See www.engineeringtoolbox.com/convective-heat-transfer-d_430.html for the range of the free air convection coefficient.