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Compressed liquid speed of sound measurements of *cis*-1,3,3,3-tetrafluoroprop-1-ene (R1234ze(Z))

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ABSTRACT

In this paper, 38 speed of sound measurements in the compressed liquid phase of a high purity sample of the novel alternative working fluid *cis*-1,3,3,3-tetrafluoroprop-1-ene (R-1234ze(Z)) are reported along five isotherms, ranging from 273.15 K to 333.15 K for pressures up to 25 MPa. The experimental technique is based on a *double pulse-echo* method resulting in an expanded uncertainty less than 0.05% at the 95% confidence level over the entire thermodynamic space.

Mesures de la célérité sonore de liquide comprimé de cis-1,3,3,3-Tétrafluoroprop-1-ène (R1234ze(Z))

Mots clés : Liquide comprimé ; Haute pression ; R1234ze(Z) ; Célérité sonore

1. Introduction

Over the last 10 or so years, there has been increased interest in low global warming potential (low-GWP) working fluids, such as propellants, solvents, foam blowing agents, refrigerants, and in high-temperature heat pumping applications and Organic Rankine cycle (ORC) applications. This interest has been driven by regulations, legislation, taxing schemes, and a change in public perception. One family of working fluids that has

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Nomenclature

p	pressure
v	volume
T	temperature
w	speed of sound
a_{ij}	coefficients of the polynomial
M	degree of pressure component in the polynomial
N	degree of temperature component in the polynomial
ΔL	difference of the acoustic path length
τ	time of flight
u	absolute uncertainty of a quantity

received considerable interest and focus is halogenated olefins, particularly, fluorinated propene isomers (see, e.g., Brown, 2009; Brown et al., 2010; and other similar example papers too numerous to mention here). One fluorinated propene isomer possessing a normal boiling point temperature appropriate for high-temperature heat pumping applications and low-temperature Organic Rankine cycle applications is *cis*-1,3,3,3-tetrafluoroprop-1-ene, also indicated as R1234ze(Z) (see, e.g., Brown et al., 2009). Akasaka et al. (2014) developed a high-accuracy fundamental Equation of State (EoS) for R1234ze(Z) valid for pressures less than 6 MPa, based on experimental values of vapor pressures, saturated liquid and vapor densities, pvT data in the liquid and vapor phases, and vapor phase sound speeds. The reader is referred to Akasaka et al. (2014) for references to the papers which report the above mentioned experimental measurements. To the best of the authors' knowledge, there are no experimental speed of sound measurements in the compressed liquid phase of R1234ze(Z) that have been reported in the publicly available literature. Therefore, this paper wishes to contribute to the characterization of R1234ze(Z) by reporting speed of sound measurements in the compressed liquid phase. The hope is that these data will prove useful for developing more refined and accurate formulations of EoS for R1234ze(Z), which will assist researchers and industry in further developing this alternative low-GWP working fluid.

2. Experimental section

The test sample of *cis*-1,3,3,3-tetrafluoroprop-1-ene (R1234ze(Z), $CF_3CH = CHF$; CAS number 29118-25-0) was provided by Central Glass Co., Ltd. with a declared purity greater than 0.99 in mass fraction. Since the effects of impurities of this order of magnitude on speed of sound measurements are negligible when compared to other sources of uncertainties, no further analysis or purification were attempted on the sample.

2.1. *Principle and apparatus for speed of sound measurements*

In the present work, compressed liquid speed of sound measurements were taken by employing an advanced transient technique, in particular the double *pulse-echo* technique (Trusler, 1991). This method is based on the determination of the time needed by an acoustic wave packet to travel a known distance in a fluid sample. In particular, an electric tone-burst is used to excite a piezoelectric (PZT) source generating two ultrasonic signals which propagate in opposite directions while spreading into the sample, which is maintained at a fixed thermodynamic state. The electrical signal has the form of a five cycles repeated tone-burst with an amplitude of 10 V_{pp}. A detailed description of the complete apparatus, and of the experimental technique, can be found in Lago et al. (2006).

The experimental apparatus was an improved version of the system described previously in Benedetto et al. (2005) and in Giuliano Albo et al. (2013). In particular, for measurements made in a compressed liquid (therefore with sound speeds typically below 1000 $m \cdot s^{-1}$), it is of fundamental importance to carefully choose the dimensions of the sensor. In this work, the sensor was constructed from 316 L stainless steel with two spacer tubes with nominal lengths of 67 mm and 45 mm, with inside and outside diameters of 25 mm and 33 mm, respectively (see Fig. 1). Acoustic path lengths were chosen in combination with the source diameter of 7 mm and the tone-burst carrier frequency of 4 MHz. Using this combination, *near-field* effects are avoided and time-of-flight measurements are independent from the chosen frequency up to 5 MHz. By using 4 MHz, it is possible to measure speeds of sound down to 500 $m \cdot s^{-1}$. Furthermore, the chosen lengths represent an acceptable trade-off between shorter distances, which reduce wave damping and accuracy, and longer trajectories, which increase wave damping and accuracy. Shorter cells are not recommended for measurements in compressed liquids because, depending on the source diameter, it is possible to fall into geometrical configurations in which wrong, but repeatable, time-of-flight evaluations are possible. The acoustic path length difference of the cell was determined in ambient conditions by calibration with degassed Millipore ultra-quality water at $T = 298.15$ K and $p = 0.1$ MPa against the speed of sound given by the 1995 EoS formulation of the International Association for the Properties of Water and Steam

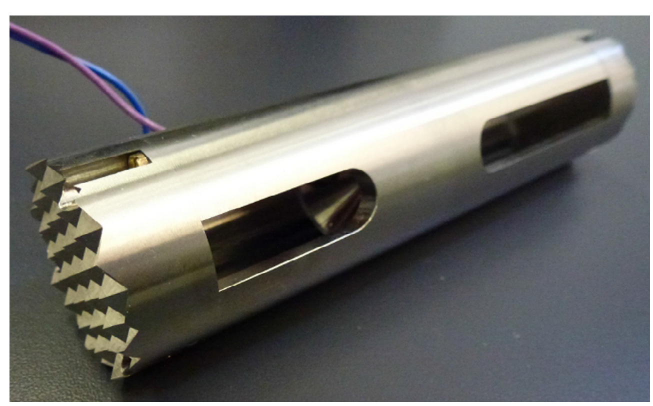

Fig. 1 – Sensor used for speed of sound measurements in compressed liquids. Different path lengths are revealed by the asymmetry of the loops. Pyramids, on the outer surfaces of the reflectors, prevent the transmitted signal to return to the receiver, interfering with the main signal.