2024 IAPWS Helmholtz Award Lecture: From Accurate Viscosity Measurements to Wide-ranging Viscosity Formulations including the Near-critical Region Applying a Structural-optimization Method

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The exact knowledge of thermophysical properties of working fluids with industrial importance is needed to develop energy efficient components like compressors, gas turbines, and gas pipelines as well as cooling, air-conditioning, and heat-pump cycles. Transport properties are not sufficiently well known, particularly in the region near to the critical point, if compared with thermodynamic properties. In addition, algorithms for the calculation have to be adequately provided for the use by engineers.

Experimental works were performed using simultaneously a vibrating-wire viscometer and a single-sinker densimeter. This enabled the evaluation of the experimental viscosities without the need of accurate equations of state to calculate densities and resulted in standard uncertainties in viscosity of ≤ 0.3% and in density of ≤ 0.1%. The measurements were carried out on the fluids helium, nitrogen, normal butane, and isobutane in the temperature range from 273 K to 498 K and at pressures up to 30 MPa including the near-critical region (< 1% above the critical temperature). Similar measurements were carried out in the same working group on ethane and propane.

Based on a physically correct critical enhancement of the viscosity data and its good agreement with theoretical predictions, a special term form for its description was developed. In the case of the density data for normal butane and isobutane, the new measurements update the data base in the near-critical region and should be used for an update of the reference equations of state. Finally, the results of the viscosity and density measurements allow modelling the critical enhancement of viscosity with guidance from the experiment.

New reference formulations for the viscosity in the complete fluid range were developed for ethane, propane, normal butane, and isobutane, based on a thorough evaluation of the data from the literature and on the new experimental data. A stepwise linear regression technique was set up to optimize the functional form of a formulation for a transport property. Theoretical guidance was included according to the kinetic theory of dilute gases, to the Rainwater-Friend theory of moderately dense gases, and to the crossover function of the mode-coupling theory for the near-critical region, concerning essential ranges of the viscosity formulations. Furthermore, the viscosity formulations show a reasonable physical behavior in the two-phase region and are characterized by a reliable extrapolation behavior down to very low and up to very high temperatures and densities. Consequently, all formulations were implemented into the NIST database REFPROP.

Finally, work on IAPWS Advisory Note No. 5 and on algorithms for calculating thermophysical properties of humid air closes the circle to the properties of water and steam.