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Experimental *n*-butane viscosity data are presented for temperatures from 100° to 340° F. and pressures from atmospheric to 8000 p.s.i.a. The data are compared with literature values and methods for correlation are discussed. A "Table of Recommended *n*-Butane Viscosity Values" for temperatures from 100° to 460° F. and pressures from atmospheric to 10,000 p.s.i.a. is presented. The recommended values were determined from the experimental data, available literature values, and the discussed correlation methods.

THE NEED for expanded information on the thermodynamic and physical properties of hydrocarbon fluids is well known. This investigation is one of several recent efforts by the authors to provide new viscosity data for pure hydrocarbons and mixtures. The results of the ethane and propane investigations and tables of "recommended" viscosity values for engineering work have been presented (5, 14). A detailed study of the viscosity behavior of ethane, propane and *n*-butane in the vicinity of their critical points has also been reported (13). Pentane is under investigation (6).

The experimental data presented extend the pressure-temperature-viscosity field for *n*-butane to temperatures above the critical temperature and pressures up to 8000 p.s.i.a. These data are compared with values previously reported in the literature. The dependence of residual viscosity on density is again shown to yield good rectification of the data for densities greater than 0.10 gram/cc. The residual viscosity concept and the kinetic theory are used to extrapolate the data to elevated temperatures and pressures with an accuracy believed within $\pm 2\%$. Recommended values for *n*-butane viscosity are presented for temperatures from 100° to 460° F. and pressures from atmospheric to 10,000 p.s.i.a.

APPARATUS AND MATERIALS

The experimental data defining the viscosity behavior of *n*-butane were obtained utilizing a capillary tube viscometer previously described in detail (4). An improved method is employed to obtain the pressure differential causing flow (4). This facilitates use of the instrument for materials in the liquid phase.

Exploratory data obtained for nitrogen at ambient temperature and 1000 p.s.i.a. did not differ significantly from the accepted value of Michels and Gibson (8) upon application of the *t*-test at the 95% confidence level. The mean of the calculated values for 31 separate measurements was 192.0 micropoises with a standard deviation of ± 0.6 micropoise, well within the 95% confidence range of 192.0 ± 1.2 micropoises. To obtain an estimate of the accuracy of data obtained using this viscometer, the errors possibly introduced by errors in measurements of the characteristic dimensions of the instrument were analyzed. This analysis indicated the maximum error of a calculated value due to errors in these measurements to be near $\pm 0.5\%$.

Because of the agreement with the accepted nitrogen value and the results of the error analysis, values obtained using the viscometer should be within $\pm 0.5\%$ of the true viscosity for those pressure-temperature regions for which $(\partial\mu/\partial T)_P$ or $(\partial\mu/\partial P)_T$ are not exceptionally large. The use of the instrument is not restricted as these derivatives are large only near regions of phase transition or in the vicinity of the critical density.

The *n*-butane used was Phillips Petroleum research grade, certified 99.9 mole % pure. No impurities were detected by mass spectrometer analyses.

EXPERIMENTAL DATA

The majority of the data are for the liquid phase, because of the relatively high critical temperature of *n*-butane; 305.6° F. and 550 p.s.i.a. Liquid *n*-butane viscosity data were obtained for pressures up to 8000 p.s.i.a. for 100° and 160° F., to 6000 p.s.i.a. for 220° F. and to 2000 p.s.i.a. for 280° F. Gas-phase data were obtained at each test temperature above 100° F. For 340° F., eleven data points for pressures from 100 to 1000 p.s.i.a. define behavior from very low densities to beyond the critical density. Extensive data were not required for all regions, particularly for high-density regions. In general, data were obtained only to the extent that quantitative analyses could be carried out. Isotherms and isobars of *n*-butane viscosity are presented in Figures 1, 2, and 3. Extensions of the curves beyond the experimental points indicate behavior determined by estimation methods which will be discussed later. For clarity, data for 14.7, 200, and 300 p.s.i.a. have been omitted from Figures 1 and 2. Detailed tables of the experimental data have been prepared and are available from ADI.

COMPARISON WITH LITERATURE

Comparatively few investigations of the viscosity behavior of *n*-butane have been reported. The maximum pressure for previous data is 2000 p.s.i.a. Sage, Yale, and Lacey (11) obtained data for five temperatures from 100° to

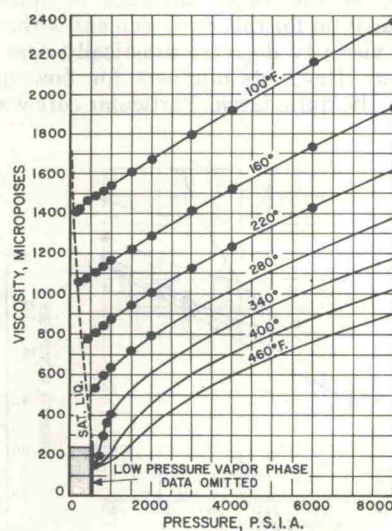


Figure 1. *n*-Butane viscosity vs. pressure

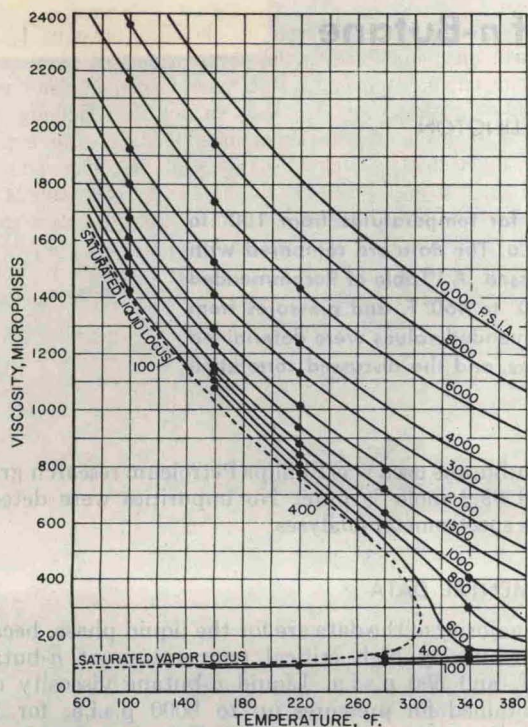


Figure 2. *n*-Butane viscosity vs. temperature

220° F.; those for 100°, 130°, 160°, and 190° F. extend from atmospheric pressure to 2000 p.s.i.a. while those for 220° F. extend only to the vapor pressure, 241 p.s.i.a. Atmospheric pressure values have been reported by Titani (16) and by Kuenen and Visser (16). Saturated liquid viscosity data have been reported by Lipkin, Davison, and Kurtz (7) for temperatures from -100° to 100° F., and by Swift, Lohrenz, and Kurata (15) for temperatures from 68° to 212° F.

The data of other investigators generally differ from the new data by less than the uncertainty the other investigator has claimed for his values. The atmospheric pressure data of Titani and Sage, *et al.* differ from the authors' data by less than 2% for most points, Figure 4. There is somewhat greater disagreement between the rolling-ball data of Sage, *et al.* and our values for some vapor phase points at higher pressure. The rolling-ball viscometer is a relative instrument. It has severe limitations for fluid regions of low viscosity and high specific weight where Reynolds number corrections become large. Their values exceed ours at 100 p.s.i.a., and the differences at a given temperature increase with pressure as the vapor pressure is approached. A possible explanation for this disagreement is that isotherms of kinematic viscosity decrease drastically near the vapor pressure. Thus, Reynolds numbers for flow under these conditions can be quite large. Particular care was exercised

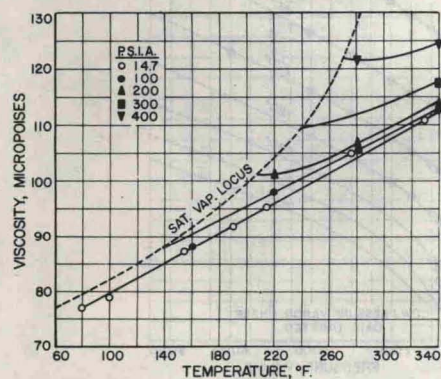


Figure 3. *n*-Butane viscosity vs. temperature at low pressures

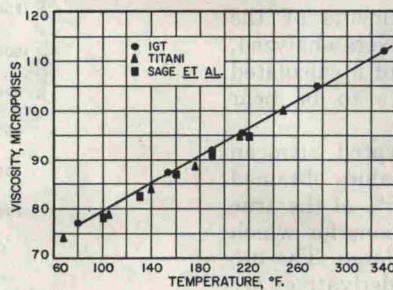


Figure 4. Comparison of atmospheric pressure *n*-butane data

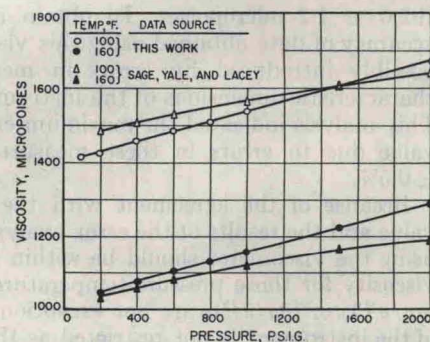


Figure 5. Comparison of liquid *n*-butane viscosity data

to ensure that laminar flow prevailed during our measurements. Therefore, it is felt that our values for this region have no greater uncertainty than the remainder of our measurements, so long as $(\partial\mu/\partial T)_P$ and $(\partial\mu/\partial P)_T$ are of the same orders of magnitude as for the bulk of our data. Sage, *et al.* discussed limitations inherent to the rolling-ball viscometer, and ascribed maximum uncertainties for the vapor phase of 5%, and for the liquid phase of 3%.

For the liquid phase, fair agreement between the data of Sage, *et al.* and our values was noted, as shown in Figure 5. Differences for 100° F. do not exceed 3%, and for 160° F. below 1000 p.s.i.a., differences are not significant. However, for 160° F. and 2000 p.s.i.a., the value reported by Sage, *et al.* is nearly 8% below ours. The comparison with the data of Sage, *et al.* can be summarized by stating that the two sets of values generally agree within the uncertainties ascribed by Sage, *et al.* for their values, except near the vapor pressure and at their highest pressures for temperatures above 100° F.

Excellent agreement was observed for the saturated-liquid region between the viscosity values of Swift, Lohrenz, and Kurata (15) obtained using a falling-body viscometer and those estimated from the authors' data. Differences are less than $\pm 1\%$. Greater differences were noted for the data of Lipkin, Davison, and Kurtz (7). For those points for which comparison was possible, the data of Lipkin, *et al.*, who used a specially designed glass capillary flow viscometer, are about 5% higher than the authors' values.

CORRELATION

The pressure-temperature-viscosity field for *n*-butane defined by the available data and those of the present investigation is still less complete than might be desired. The object in correlating the data was to determine "best values" for *n*-butane viscosity in the pressure-temperature region investigated, and then to extend the region accurately. This extension was affected using only techniques which correlated accurately the data of the experimental investigation.

Experimental viscosity data are usually obtained for a range of pressures while maintaining constant temperature. Thus, isotherms of viscosity can be constructed as functions of pressure as experimental data are obtained. If data for a sufficient number of temperatures are obtained, isobars of viscosity can be constructed as functions of temperature. The isobaric plot will generally indicate inconsistent isothermal values. Use of both plots permits the presentation of a consistent set of viscosity values for the region investigated. Interpolated values read from the isothermal and isobaric plots should be as accurate as the experimental data if sufficient data are obtained, but extrapolations of the isotherms or isobars would yield values for which realistic estimates of accuracy would not be possible.