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Viscosity of Water and Steam at High Temperatures and High Pressures

Akira NAGASHIMA (長 島 昭)

Introduction

Among various fluids important for industrial purposes, water (steam) is suitable for many usages and strong demand for precise investigations of properties of water and steam at high temperatures and high pressures exists especially in the field of power industries. Although equilibrium properties (thermodynamic properties) of ordinary water substance have been studied to a comparatively sufficient extent, the experimental studies of non-equilibrium properties (transport properties) in wide range of temperature and pressure only started recently. In addition to the industrial interest, water substance often attracts physicist's attention because of its peculiar behavior, which can not be estimated from other substances.

In this investigation, the experimental study on one of important non-equilibrium properties, viscosity, has been carried out in the wide range of temperature up to 900°C and pressure up to 1000 bar (1025 kg/cm²).

Chapt. 1. Purpose of This Investigation and Review of Experimental Methods

After the critical analyses of the various methods for viscometry, it is revealed that the most reliable method is that of the capillary.

Chapt. 2. Historical Review of the Viscosity Investigations of Water and Steam

The detailed historical review of experimental investigations as well as some theoretical approaches are given in this chapter. They show strong necessity of the experimental study of viscosity especially in the high temperature and high pressure region.

Chapt. 3. Experimental Study of the Viscosity of Water and Steam

The capillary method was used as the measuring method because of the high reliability. A closed circuit viscometer with a platinum capillary was designed and constructed in order to operate at high temperature and high pressure. The used capillary is made of platinum-rhodium (5%) alloy, and has the diameter of 0.27 mm and the length of 300 mm. Main part consisted of the platinum pipe system is put in the autoclave made of heat-resisting steel and is heated up by the electric furnace from outside through a thick-walled cylindrical thermostat made of copper. The whole system is pressurized by a plunger pump to high pressure and the pressure of the fluid is measured by a standard deadweight gauge.

The flow rate of the fluid is measured by the specially-designed constant-flow apparatus with the coupled cylinders. For the measurement of the pressure drop between both ends of the capillary, a precision U-tube manometer of mercury was designed and used at high pressure.

Viscosity was calculated using the following modified Erk's equation:

$$\eta = \frac{\pi C}{8L} \cdot \frac{1}{Q} \cdot \frac{P_1^2 - P_2^2}{2P_1} \left(1 + \frac{4\zeta}{r}\right) (1 + 3\alpha \Delta t) - \frac{\rho Q}{8\pi L} \cdot \frac{\left(m + \ln \frac{P_1}{P_2}\right)}{(1 + \alpha \Delta t)}$$

where C , Q , L , P , ζ , r , α , Δt , ρ and m are the capillary constant, the flow rate, the capillary length, pressure, the slip correction factor, the capillary radius, the thermal expansion coefficient of the capillary material, temperature ($t - 20^\circ\text{C}$), density of the fluid and the kinetic energy correction factor, respectively and suffix 1 and 2 correspond to the entrance and the exit of the capillary. Various corrections and density by the new international equation of state were calculated by means of an electronic computer.

After the various preliminary experiments to check the flow conditions, main experiments were carried out and the results with the satisfactory precision have been obtained, which show the characteristics of the each isotherm. About 260 measured data have been obtained in the high pressure region of up to 900°C and in the region near the critical point, in the latter only few data were exist in the former literatures. From the measured results such new facts have been shown, as that the so-called excess viscosity is the function of not only density but also of temperature in the steam region, that the viscosity of water changes quite largely with the pressure change in the narrow region close to the saturation pressure, and so on.

In this investigation, extreme care was taken to calibrate the capillary. All measurements were done with Reynolds number of less than 300 which was found to be the critical for a metallic capillary of the rough surface, while most of other investigators supposed the critical Reynolds number to be about 2000 also for the metallic capillaries.

Chapt. 4. New Correlation of the Viscosity of Water and Steam

Based upon the results of the experimental investigations, a new equation of viscosity for water and steam has been correlated as follows:

$$\eta = a_1 + a_2 t + a_3 \rho + a_4 \rho^2 + \frac{a_5 \rho (1 - \rho)^4}{1 + t + a_6 t^4} + \frac{a_8 \rho}{(t + a_7)^3 \{(1 - \rho)^2 + a_9\}}$$

where a_i are constants.

This equation expresses the viscosity of water and steam with a single function of temperature and density in the wide range of temperature up to 1000°C and

pressure up to 1000 bar. Only 9 constants are included in this equation, which is simpler than those of other investigations. With this new equation, the critical comparisons of the measured data in the former literatures have been carried out and also the calculated values by the Enskog's equation have been compared. Then it is found that the Skeleton Table values of 1964 are too high in the region near 400°C, 200 bar, and that the calculated values by the Enskog's semi-theoretical equation can be relied upon for the practical purposes in the region of $T/T_c > 1.4$, where T is temperature and T_c is the critical temperature in °K.

Chapt. 5. Conclusion

This investigation revealed the viscosity behavior of water substance in the high temperature and high pressure region, which had been not satisfactorily known formerly, and gives the consistent set of experimental data as well as the correlation for the wide range of temperature and pressure. One major reason of the discrepancies existed among former investigations in the steam region was explained as the difference of their calibration methods.

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