Viscosity and Density Measurements of High Temperature Melts

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2.1 Introduction

Since the viscosity and density are most fundamental properties for any fluids, many efforts to obtain reliable values have been made. However, the measurements are not so easy, especially at high temperature in molten state. The high temperature melts are typically classified into molten metals, molten salts, and molten oxides. They appear in many industrial processes, for example, steelmaking, nonferrous metallurgy, aluminum smelting, foundry, glass making, etc. The adaptable methods for the measurements should be chosen carefully by considering some physical and chemical properties of the melt. Iida published the review on the properties including viscosity and density of molten metals [1], and the comparison among the viscosities of molten iron reported by many researchers showed considerable difference of several dozen percent. The viscosity value is in considerably wide range depending on the groups of the melts, for example, in general low for molten metals and high for molten silicates, including slag and glass, and the difference reaches more than ten orders by reflecting the difference in the melt structure. On the other hand, density is mainly depending on atomic mass and not so different to each other because of not so big difference in molar volumes of the components. Various methods for viscosity and density measurement were also introduced [2] and also the viscometries were summarized [3].

2.2 Viscosity Measurement

Viscosity of the liquid decreases with an increase of temperature. The temperature dependence obeys Andrade law, which is similar to Arrhenius behavior as shown in (2.1).

\[ \eta = A \exp\left(\frac{E}{RT}\right). \]  

(2.1)
The typical methods used for viscosity measurement are a capillary method, an oscillating method, a rotating method, etc. Although it is difficult to adapt them to some liquids with non-Newtonian behavior, there are almost no problems because most high temperature melts show Newtonian behavior. The capillary method, which is used as the prescriptive method at room temperature, is simple and very precise in relatively wide viscosity range, although the application at high temperature is limited due to the problem in the use of refractory materials for apparatus and the difficulty for detecting meniscus. However, the successful application was reported on high temperature molten salts [4]. The oscillating method, especially an oscillating cylinder method [5], is also precise and sensitive although the measurable viscosity is limited in lower range. The big advantage of oscillating method is in wide selection of the container material. Therefore, it is used for high temperature melts with low viscosity such as most of molten metals and many molten salts. The rotating method [6] is suitable generally for high viscosity range because it contains power train as the driven device with friction loss. The method is suitable for measuring the viscosity of molten glass and slag.

### 2.2.1 Capillary Method

Principle of the capillary method is simple. The viscosity, $\eta$, is expressed by well known Hagen–Poiseuille’s equation (2.2) in the case of vertical type of the capillary viscometer.

$$\eta = \frac{\pi r^4 \rho gh}{8(L + nr)V} t - \frac{m \rho V}{8\pi(L + nr)} \frac{1}{t}, \quad (2.2)$$

where $\rho$ is the density of liquid, $r$ and $L$ are the radius and length of the capillary, $h$ is the effective height of the liquid column, $V$ is the volume of the liquid that has flowed, $g$ is the gravitational acceleration, $t$ is the time for the flow out of liquid, $m$ and $n$ are constants. For an identical viscometer, the coefficients of right hand terms in (2.2) except $t$ and $\rho$ are constant; therefore (2.2) is rewritten to (2.3) by introducing kinematic viscosity, $\nu$:

$$\nu = \frac{\eta}{\rho} = C_1 t - C_2 / t. \quad (2.3)$$

As the determination of the constants, $C_1$ and $C_2$ based on the apparatus dimensions in (2.2) are not realistic. They are usually calibrated by using a standard liquid of known kinematic viscosity through the measurement of the time for it to flow out of the liquid. Distilled water is most popular as a standard liquid for low viscosity due to the well known kinematic viscosity. Figure 2.1 shows a capillary viscometer made of quartz for high temperature molten salts [4]. The melt under measurement is sealed completely inside. Then the melt with relatively high vapor pressure is allowed even if it is molten AlCl$_3$ with considerably high vapor pressure and strong hygroscopicity [7]. The inner diameter and the length of the capillary were about 0.4 and 80 mm, respectively. Therefore, Reynolds number in the capillary was less