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Automated high-temperature liquid level measurement system using a dynamic tube pressure technique

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An in-house manufactured liquid level measurement system based on dynamic tube pressure measurements was established for high-temperature corrosive molten salts. The accuracy and precision of the present technique depend on the furnace temperature, initial base tube pressure, and tube speed. Whereas the initial base tube pressure did not influence the performance of the measurements significantly, a set value of the critical pressure level for the detection of the liquid surface was an important factor, especially in case of the higher temperature experiments. Within a temperature range of 773–1073 K using KNO_3, our technique could obtain a measurement error of less than ca. 0.05 mm in precision. The tube speed increased from 0.25 mm s^{-1} to 2.00 mm s^{-1}, resulting in a % departure of only 1.1%, 1.3%, and 1.9% at 773 K, 973 K, and 1073 K, respectively. The measurement of travel distance instead of measuring the liquid level is useful in terms of the calibration-free process monitoring. The gravimetric calibration method was also used to determine the total mass of the liquid, where the weight versus travel distance calibration curves showed an excellent linearity with $R^2 = 0.9999$ under all temperature conditions.

Introduction

The measurement of the liquid level in industrial processes is important for process monitoring and control. A liquid level measurement is also crucial in regard to nuclear material accountability [1–4]. Once the liquid level is measured, the liquid volume can be obtained, and then the total mass of the materials present in a vessel can be determined using the information on the predetermined solution density. A number of level measurement techniques such as floats, dip probes, sight gauge glasses, displacers, magnetostrictive devices, resistance tape, rotation suppression methods, servo powered level gauges, vibrating fork switches, capacitance methods, conductivity methods, thermal dispersion techniques, ultrasonic gap sensors, guided wave radar, time domain reflectometry, non-contacting radar, gamma-ray radiation absorption methods, and single digital cameras have been developed for many years. However, there is no single method applicable to all field processes owing to the limitations depending on the process environment and conditions [5–9]. Thus, special care should be taken in the selection of a method by considering the characteristics of the processes and the applicability of each technique under each specific process condition. For example, in aqueous nuclear fuel reprocessing facilities operating mostly at ambient temperatures, the typical standard liquid level monitoring instrument for the nuclear material accountancy is a static bubbler [10]. However, in the pyroprocess under active development in Korea and the US for recycling spent nuclear fuels, highly-corrosive molten salts at high temperatures are handled inside the argon-atmosphere glove box using special equipment. In such harsh environment processes, various methods such as floats, electrical conductivity probes, heated thermocouples, radar-based detectors, and bubblers have been considered as a potential standard level monitoring method [11–18].

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Among the many level measurement techniques, pressure-based methods such as a hydrostatic pressure method, a differential pressure method, and a static bubbler method have certain advantages because not only is a continuous level measurement with an inexpensive and simple design possible, but the density can also be determined simultaneously. While the hydrostatic pressure method and the differential pressure method require the pressure sensors be in direct contact with the liquid, the bubblers use two tubes [17], which instead of the sensors have direct contact with the liquid at all times during an operation, and therefore hot chemically-reactive liquids can damage the tubes. Thus, special care must be taken to deal with such a liquid with regard to liquid level measurements. Moreover, the major disadvantages of all three conventional pressure-based methods are an excessive dependency on the density, the inhomogeneity, and conditions of the liquid medium.

Recently, we developed a new liquid level measurement technique based on the dynamic tube pressure method [19]. Compared to the conventional static bubblers, our dynamic tube pressure method detects the liquid surface directly by using a vertically moving tube connected to the pressure sensors detecting the abrupt internal tube pressure changes in the tube within a very short period of time so that the direct contact with a liquid solution can be minimized. In this study, we proposed an automated pressure-based liquid level measurement technique suitable for very hot, corrosive, highly radioactive environments through the improvement of our prototype dynamic pressure-based level measurement system. The effect of temperature, density, composition, and homogeneity of the bulk solution can be eliminated as well because the travel distance of the tube in our present technique depends only on the conditions of the liquid surface and not on those of the bulk. In order to examine the applicability of our in-house manufactured level measurement system, a variety of experimental parameters affecting the precision and accuracy of the measurement system have been investigated with hard-to-handle hot and corrosive chloride molten salts.

Experimental

The picture of a high-temperature dynamic tube pressure measurement system is shown in Fig. 1. The measurement system consists of differential pressure sensors, a computer-controlled linear stepper motor (EMS24-C1036, E-Motor, Republic of Korea), and a type 304 stainless steel tube (custom-manufactured 10-cm long with I.D. = 0.85 mm, Daejin Co., Republic of Korea) connected to an argon gas cylinder. Pressures inside the tube were monitored using a differential pressure switch and transmitter (PTA 202D-D2-D300P, CSC Co., Republic of Korea). The flow and pressure of argon through the tube is controlled by a needle valve from an argon gas cylinder.

A high-temperature vessel for molten salts was placed inside the electrical furnace. Potassium nitrate (KNO_3) was purchased from Sigma-Aldrich Co. and used as obtained. KNO_3 powders were placed into the cylindrical vessel with a diameter of 2 cm and a length of 8 cm. A gravimetric calibration technique was performed to determine the total mass of the solution. In the gravimetric calibration technique, various amounts of KNO_3 granules were weighed using a digital balance with 0.01 g readability, and added to the vessel so that the liquid level was accurately increased. Before measuring the liquid level, the liquid temperature of the KNO_3 molten salts was measured by dipping the glass-sheathed thermocouple into the melts.

The setting temperature of the temperature controller was varied from 773 K to 1073 K for an examination of the temperature effect on the ambient air pressure above the liquid and the measurement performances. The actual temperatures at the top and bottom of the vessel with and without molten salts were measured to examine the effect of temperature gradient inside the vessel.

The tube is brought to the surface of a thermostat molten salt in the hot vessel by means of a stepper motor for precise positioning control. The stepper motor is controlled by a programmable logic controller (XGB Cnet I/F, LS Industrial Systems Co., Republic of Korea) combined with a National Instruments (NI) LabVIEW program (custom written by Quantum Software, Republic of Korea) running on a personal computer controller. The program scripts send commands to the serial ports (RS485) of a PC installed with millisecond accuracy. Fig. 2 shows the basic circuit block diagram for the level measurement system. A stepper motor with a resolution of 1.8°/pulse drives a stainless steel tube in a downward direction at speeds of 0.25–2.00 mm s^{-1} over a 10–30 cm distance. The stepper motor's angular increment of 1.8°/pulse resulted in a

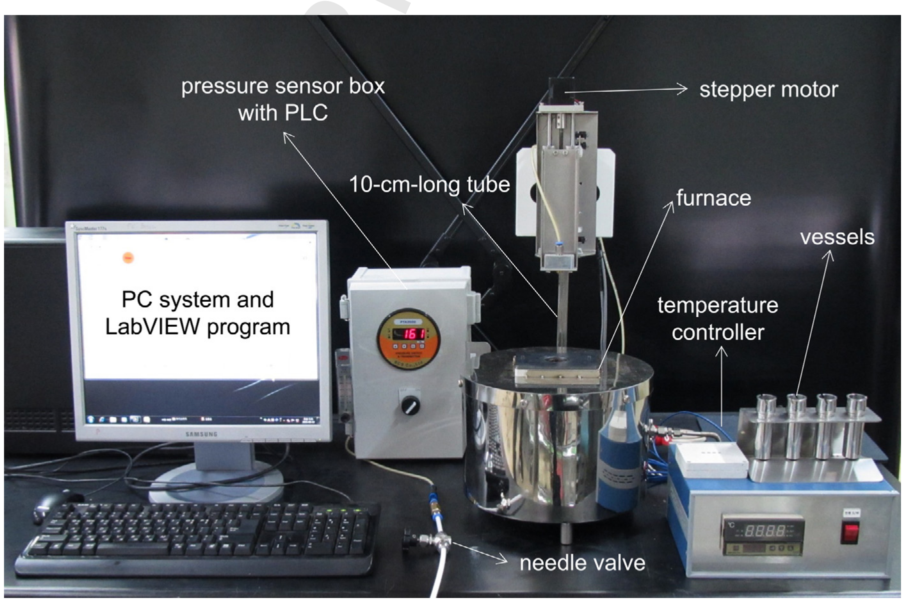

Fig. 1. A picture of the high-temperature liquid level measurement system based on the dynamic tube pressure measurement equipped with a stepper motor controlled by a program logic controller (PLC) and the LabVIEW program, a differential pressure sensor, a needle valve, a high-temperature furnace, and temperature controllers.

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