Quantitative Evaluation of Carbon Black Dispersion for High-Quality UCO Kernel Fabrication

Minseok Lee, Injin Sa, Yeon-Ku Kim, Eung-Seon Kim*

Advanced Nuclear Fuel Technology Development Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, Republic of Korea 34141
**E-mail: kimes@kaeri.re.kr*

Keyword: HTGR, UCO kernel, Carbon black dispersion

1. Introduction

High-temperature gas-cooled reactors (HTGRs) are regarded as one of the advanced Generation VI reactors with the capability for carbon-free hydrogen production. HTGRs utilize tri-structural isotropic (TRISO) fuel, consisting of UO_2 or UCO kernels, a carbon buffer, an inner pyrolytic carbon (IPyC) layer, a silicon carbide (SiC) barrier, and an outer pyrolytic carbon (OPyC) layer to prevent the release of fission products.

Historically, UO_2 was initially employed as the fuel kernel. However, significant problems emerged because of CO gas generation resulting from the reaction between UO_2 and the carbon coating layers [1]. The most representative phenomenon is the so-called amoeba effect, in which the UO_2 fuel kernel migrates from lower-temperature to higher-temperature regions. This occurs because the CO(g) phase present at high temperatures condenses into C(s) + CO_2(g) at lower temperatures. Furthermore, CO gas is known to overpressurize the fuel kernel, which may result in the fracture of the SiC layer, or chemically attack the SiC layer, thereby degrading the integrity of the coating layers. To address these issues, a UCO kernel—composed of mixed UO_2 and UC_2 phases—was proposed. It has been demonstrated that incorporating only about 20% UC_2 can significantly reduce CO release, thereby enhancing the stability of TRISO fuel at high temperatures.

The UCO kernel is produced through the carbothermic reduction reaction between UO_2 and carbon, in which carbon black serves as the carbon source [2]. To obtain high-quality UCO kernels, uniform dispersion of carbon black in the broth solution is essential prior to internal gelation. Agglomeration can lead to voids in the kernel, preventing it from reaching the theoretical density. So far, it has been reported that the agglomerate size of carbon black should be below 5 μm, and preferably around 1 μm, in order to obtain higher-quality UCO kernels [3]. However, a wide range of carbon blacks is commercially available, and each type exhibits unique dispersion characteristics. For example, upon dispersion in aqueous media, the particle size distribution may be unimodal or multimodal, with distribution widths varying from narrow to broad. In order to ensure consistent production of high-quality UCO kernels, it is necessary to establish more quantitative and well-defined criteria for carbon black dispersion. In this study, a preliminary investigation was carried out by varying the dispersion conditions of carbon black and measuring the resulting properties to establish quantitative indicators.

2. Methods and Results

2.1. Preparation of carbon black dispersed solution

Two commercially available carbon blacks were prepared, designated CB-1 and CB-2. CB-1 is partially oxidized carbon black containing approximately 5–10% volatile content, with primary particle sizes of 8 nm. By contrast, CB-2 is a surface-modified carbon black that has been chemically treated to allow dispersion in water without a dispersing agent. Following the conventional UCO kernel fabrication process, carbon black was dispersed in a 3.2 M HMTA–urea solution. The dispersion concentration was set to give an [HMTA–urea]/[C] ratio of 1.3 [4]. Dispersion was carried out by 500-W ultrasonication. For CB-1, 7 wt% of a dispersing agent (Tamol SN) was added, whereas CB-2 was dispersed without dispersing agents.

2.2. Particle-size Distribution

The particle-size distribution (PSD) of carbon black dispersions provides the most intuitive quantitative metric. The degree of dispersion was controlled by varying the ultrasonication duration (10, 30, and 60 min), and the PSD was measured by laser diffraction using Mie theory.

CB-1 exhibits a bimodal particle-size distribution (Fig. 1), with small agglomerates in the 0.01–0.1 μm range and large agglomerates in the 0.2–20 μm range. As the degree of dispersion increases, the fraction of small agglomerates grows while that of large agglomerates diminishes. Accordingly, the volume-median diameter

Dv(50) decreases markedly from 3.88 μm to 0.037 μm. In addition, the volume-based 90th percentile diameter Dv(90) decreased significantly from 13.3 μm to 3.18 μm.

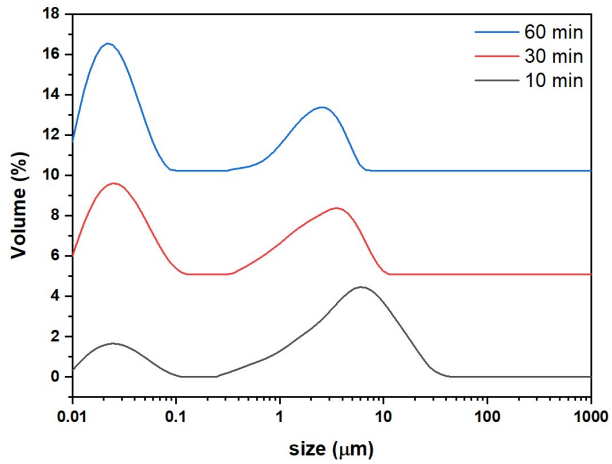

Fig. 1. Particle-size distribution of the CB-1 suspension as a function of ultrasonication duration.

Unlike CB-1, CB-2 exhibits a clearly uniform (unimodal) size distribution (Fig. 2). This behavior is likely due to the hydrophilic polymer grafted onto the carbon black surface, which suppresses the formation of large agglomerates. Dv(50) shows minimal change (0.0279 → 0.0234 μm), suggesting that effective dispersion is achieved after just a few minutes of sonication. Additionally, Dv(90) decreased from 0.0621 to 0.0417 μm, and the distribution peak became sharper.

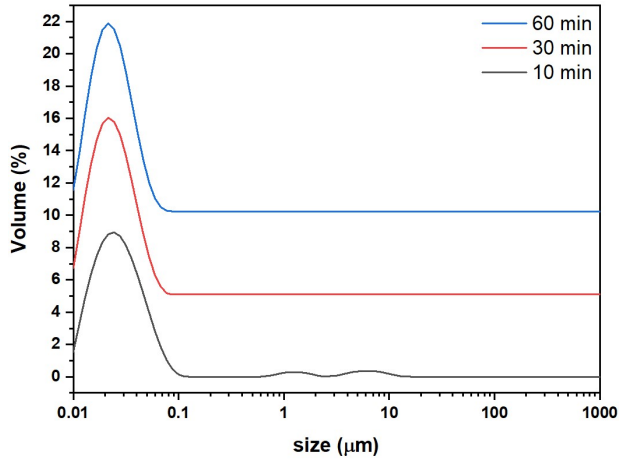

Fig. 2. Particle-size distribution of the CB-2 suspension as a function of ultrasonication duration.

3. Conclusion

This work explores quantitative indicators for assessing carbon black dispersion for optimal UCO-kernel production. We evaluated PSDs under varying dispersion conditions in HMTA–urea solution and observed clear shifts in metrics (e.g., Dv(50)) depending on carbon black type and sonication time. In future work, UCO or surrogate ZrCO kernels will be fabricated under the selected carbon black dispersion conditions, and their properties will be correlated with the proposed quantitative indicators.

Acknowledgement

This work was supported by the Korea Atomic Energy Research Institute R&D program (Contract No. 521410–25).

REFERENCES

[1] A. Sowder, C. Marciulescu, Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance, Topical Report EPRI-AR-1 (NP), Technical Report, 2019.
[2] D. P. Stinton, W. J. Lackey, and R. D. Spence, “Production of spherical UO_2-UC_2 for nuclear fuel applications using thermochemical principles,” Journal of the American Ceramic Society, vol. 65, no. 7, pp. 377–382, 1982.
[3] C. I. Contescu, F. S. Baker, R. D. Hunt, J. L. Collins, and T. D. Burchell, Selection of water-dispersible carbon black for fabrication of uranium oxicarbide microspheres, J. Nucl. Mater., vol. 375, no. 1, p. 38, 2008.
[4] C. M. Barnes, W. C. C. Richardson, D. W. Husser, and M. Ebner, Fabrication process and product quality improvements in advanced gas reactor UCO kernels, 2008 Proc. 4th Int. Top. Meet. High Temp. React. Technol. HTR 2008, vol. 1, p.77–188, 2009.