**Overview Of Hydrodynamics And Scale-Up Of TRISO Spouted Beds Coaters**

# Thaar M. Al-Juwaya1,2\*, Neven Ali3, Muthanna Al-Dahhan2,4,5

*1 Nuclear Technologies Institute, King Abdulaziz City for Science and Technology (KACST), P.O. Box 6086, Riyadh 11442, Saudi Arabia*

*2 Nuclear Engineering and Radiation Science Department, Missouri University of Science and Technology (Missouri S&T), Rolla, MO 65409, United States*

*3 Nuclear Engineering Department, University of New Mexico, Albuquerque, NM*

*4 Linda and Bipin Doshi Chemical and Biochemical Engineering Department, Missouri University of Science and Technology (Missouri S&T), Rolla, MO 65409, United States*

*5 TechCell, Mohammed VI Polytechnic University, Lot 660, Hay Moulay Rachid 43150, Ben Guerir, Morocco.*

*Email(s):* *taljuwaya@kacst.edu.sa*

Abstract – *The quality of TRISO coated nuclear fuel particles is crucial to the successful operation and safety of Very-High-Temperature Nuclear Reactors (VHTR). For this reason, the TRISO particles should be free of defects and uniform in size and shape, as well as have a uniform coating. In this respect, the gas-solid spouted bed coating technology of TRISO particles is important. Coating layers around the fuel kernel are delicate processes impacted mainly by the hydrodynamics of the spouted beds. It becomes even more complex when considering that the success of the preceding coating affects the probability of coating the next layer successfully. As the current spouted bed coaters are relatively small, large-scale spouted beds are also essential to fabricate high-quality and large quantities of TRISO particles for the VHTRs. It is imperative to develop large-scale spouted beds in order to meet the growing demand for TRISO particles for the VHTRs. Thus, the scaling up of spouted beds is considered one of the major challenges in manufacturing TRISO nuclear fuel particles. Although the insights provided by the literature on spouted beds, scale-up of gas-solid spouted beds is still far from satisfactory. Correspondingly, having a fundamental understanding of hydrodynamics and scale-up of spouted beds dynamics is essential towards the development and commercialization of the VHTRs. In this work, a comprehensive overview of our newly developed and validated mechanistic scale-up methodology for gas-solids spouted beds based on matching the radial profile of gas holdup is presented. The overview aims at pointing out the present findings and challenges about the mechanistic scale-up methodology of gas-solids spouted beds. In addition, the overview includes a comparison between this mechanistic scale-up methodology and traditional scale-up methodology based on matching dimensionless groups to demonstrate its improved accuracy in predicting the performance of spouted bed systems.*

**Keywords:** *Very-High-Temperature Nuclear Reactors (VHTR), TRISO, Spouted beds, Scale-up, radioisotopes-based measurement techniques.*

I. Introduction

Among the new generation of nuclear reactors, Very High-Temperature Reactors (VHTRs) are most suitable for meeting the 21st century's energy demands. These reactors have passive safety as one of their most important characteristics [[1](#_ENREF_1)]. As TRISO fuel coated particles play a major role in the performance and safety of the VHTR, the fuel coating technology as well as related processes are key. Gas-solid spouted beds are used for coating the TRISO fuel particles through chemical vapor deposition (CVD). It is a very delicate and demanding process to produce the TRISO fuel coatings [[2](#_ENREF_2), [3](#_ENREF_3)]. Individual fuel particles cannot have more than one coating failure per 105 particles as required by current standards [[4](#_ENREF_4)]. It has been reported that the spouted bed coater plays an essential role in the coating process, and its hydrodynamics greatly determine the quality of the particles produced [[3](#_ENREF_3), [4](#_ENREF_4)]. As a result, it is imperative to investigate the hydrodynamic behavior of gas–solid flow in spouted beds.

As a general rule, the scale-up challenge of the TRISO spouted bed coater or gas-solid spouted bed in general hasn't been addressed to its full potential. Though spouted beds have been used for coating TRISO for many years, determining the design and operating conditions of the bed seems to be largely empirical. Spouted beds CVD processes lack fundamental knowledge that can directly be used for process optimization. Spouted beds should be used to support the commercial implementation of nuclear reactors of the aforementioned type with high-quality and large quantities of safer coated fuel particles. The present study was motivated by the necessity to conduct scale-up studies of spouted beds, complemented by advanced non-invasive measurement techniques. Even though He et al. [[5](#_ENREF_5)] defined the first scaling relationships for spouted beds using matching dimensionless groups, further investigation is still needed. Since the gas phase dictates the flow dynamics of the gas-solid spouted beds, [[6](#_ENREF_6)] and [[7](#_ENREF_7)] proposed a mechanistic scale-up methodology based on the radial gas holdup profiles. However, the knowledge of the radial gas holdup profiles requires the development of reliable experimental and numerical techniques, which is still an active research area. Additionally, further investigation is needed to study the effects of other operating parameters, such as the solids circulation rate and the gas flow rate, on the flow dynamics. According to [[6-9](#_ENREF_6)], the new method for scaling up gas-solid spouted beds is as follows:

“*when spouted beds with different sizes and/or conditions are geometrically similar and have closer (which is called matched) gas phase holdup radial profiles at a desired bed height within the developed flow region, the local dimensionless values of the hydrodynamic parameters and their trends are similarity or closer to each other in these two spouted beds at corresponding bed heights*”

As part of this work, the new scaling up methodology of spouted beds is validated and discussed by evaluating other important solid particle flow parameters using advanced radioisotope techniques, gamma ray computed tomography (CT) [[10](#_ENREF_10), [11](#_ENREF_11)] and radioactive particle tracking (RPT) [[12-15](#_ENREF_12)]. As a result, solid particle flow in spouted beds can be better understood and future applications can be enhanced.

II. Description of the actual work.

In all experiments, conventional spouted beds, or conical-cylindrical spouted beds, were used at two different scales. The experiments were conducted with both laboratory- and pilot-scale spouted beds to assess the scale-up methodology. They have inner diameters of 0.076 m and 0.152 m, respectively, for the small and large spouted beds. Designed geometrically similar, both spouted beds were made of Plexiglas. In previous studies [[8](#_ENREF_8), [9](#_ENREF_9), [16-20](#_ENREF_16)], similar experimental setups have been used. As shown Fig. 1., the schematic details of the two spouted beds are presented.

To validate the new scale-up methodology of gas-solids spouted beds using RPT technique, three sets of conditions were systematically designed. These sets of conditions were designed to evaluate the accuracy of the new scale-up methodology. Table 1 summarizes the three sets of conditions investigated here. As a reference case, the first set of conditions was designed for the large spouted beds. To provide a similar gas holdup profile to that obtained in the reference case, the second set of conditions was determined for the small-scale spouted beds. In the third case, gas holdup profiles were designed to be dissimilar from those obtained in the reference case. The second and third sets of conditions were designed to evaluate the accuracy of the new scale-up methodology by evaluating the results from different bed sizes. The data from these sets of conditions was compared against the data from the reference case to determine the accuracy of the new scale-up methodology.



Fig. . Schematic diagram of the small and large scales gas-solids spouted beds.

**Table 1**. Experimental conditions for similar and dissimilar gas holdup radial profiles for the hydrodynamics similarity of spouted beds identified by [[7](#_ENREF_7)].

|  |  |  |  |
| --- | --- | --- | --- |
| Condition/Case |  Reference | Similar gas-holdup profile | Dissimilar gas-holdup profile |
| Bed scale | **Large** | **Small** | **Small** |
| *Dc* (m) | 0.152 | 0.076 | 0.076 |
| *Di* (mm) | 19.1 | 9.5 | 9.5 |
| *L* (m) | 1.14 | 1.14 | 1.14 |
| *H* (m) | 0.323 | 0.16 | 0.16 |
| *T* (K) | 298 | 298 | 298 |
| *P* (kPa) | 101 | 364 | 101 |
| Particles | Glass | Steel | Glass |
| *dp* (mm) | 2.18 | 1.09 | 1.09 |
| *ρs* (kg/m3) | 2400 | 7400 | 2450 |
| *ρf* (kg/m3) | 1.21 | 3.71 | 1.21 |
| µ (x 10^5) (Pa.s) | 1.81 | 1.81 | 1.81 |
| *U* (m/s) | 1.08 | 0.64 | 0.74 |
| *Ums* (m/s)Experimental Values | 0.89 m/s | 0.58 m/s | 0.68 |
| *Ums* (m/s)Correlation prediction of [[21](#_ENREF_21)] | 0.85 m/s | 0.59 m/s | 0.68 |



Fig. . Gas-solids spouted beds inside the CT platform for scanning.

II. Results and discussions.

***II.A. Solids holdup profiles and cross-sectional distributions of the spouted beds – reference case.***

The results below (Fig. 3) illustrate how solids hold up along the dimensionless height (z/D) of the 6-inch spouted bed. According to the distribution, Z represents the actual height of measurement, while D represents the diameter of the column. It is noted that solids hold up differently in the annulus region of a spouted bed compared to the spout region. In contrast, solids holdup profiles in the annulus region along the z/D levels of spouted beds are similar. Solids in the annulus behave more like loose packing beds as they move gradually. Solids holdup decreases in the spouted bed at the lower axial height of the bed (near the gas jet) because of the increase in gas velocity. This is due to the turbulent nature of the gas jet, which generates high shear forces in the bed that cause particles to move faster and prevents them from settling. As a result, particles tend to accumulate in the annulus region, where the gas flow is more uniform and less turbulent. As a result, at the spout region, the solids increased by average percentage of 31.86 % from z/D 0.8 to 1.1, and increased by 24.63 % and from z/D 1.1 to 1.8. However, particles were less concentrated radially out from the axis of the fountain and held very slowly due to the scattering of particles. Because the particles scatter in this particular region, this is to be expected. As a result, the particles can be redirected back into the annulus via the fountain. The reason for this is due to the fact that the fountain creates a swirling motion which helps to redirect particles back into the annulus, as well as the fact that the particles are unable to move too far away from the fountain due to inertia. This causes the particles to be concentrated around the fountain, and as the fountain moves outwards the particles follow and thus the concentration of particles increases. Gamma ray computed tomography data has been processed using Alternating Minimization (AM) algorithms to determine holdup distributions. At z/D levels of 0.8, 1.1, 1.8, and 2.4, cross-sectional distributions of solids holdup were calculated for the 6-inch spouted beds (Fig. 4). On the right of the images is a scale-bar indicating the fraction of solids holdup. Red indicates higher solids holdup, and blue indicates lower solids holdup. There is a clear distinction between the spout and annulus in the color distribution of the images. There is a clear distinction between the spout, the annulus, and the fountain in the images of spouted beds. The spout and annulus regions have different solids holdup dynamics, which is reflected in the images. This is due to the different flow regimes in the two regions. The fountain region has a different solids holdup than the other two regions, indicating a unique flow regime.

|  |
| --- |
|  |
| (a) |
|  |
| (b) |

Fig. . Radial profile of solids holdup in the large spouted beds at different measuring planes (z/D) in (a) spout/annulus region and (b) fountain region.

|  |
| --- |
|  |
| (a) |
| C:\Users\tmap8b\Desktop\2rainA.jpg |
| (b) |

Fig. . Cross sectional of solids holdup along the bed height of the large spouted beds at z/D levels of (a) 0.8, and (b) 1.1.

***Similar gas-holdup profiles for gas-solids spouted beds using CT***

Based on the mechanistic scale-up methodology previously developed, [[7](#_ENREF_7)] determined a set of conditions with similar and dissimilar gas holdup profiles and implemented these conditions. For both large and small scales spouted beds, the cross-sectional distribution of gas holdup at selected levels has been measured using gamma-ray computed tomography (CT). Fig. 5 illustrates this validation, in which the cross-sectional distributions and radial profiles of the gas holdups of the pilot plant and lab scale spouted beds are similar at a selected dimensionless height. In terms of mean and standard deviation, the results indicate very similar gas holdup distributions between the reference case and the similar gas holdup profile. The similarity between the two distributions indicates that the gas-solid holdup in both cases is similar. This implies that the scaling-up process of the spouted bed from small to large scale was successful, as the method was able to replicate the results across different scales. The scaling up process is considered successful when the results of the small scale method are replicated in the large scale method. To ensure this, further evaluation of the hydrodynamic parameters needs to be done to ensure similarity between the two scales. This includes evaluating the spout diameter, cumulative probability distribution, fraction of cycle time, radial profiles of particle velocities and solids eddy diffusivity using RPT. Due to the length restriction of this contribution, only the results of the solids cycle time of the spout region in the beds for the investigated conditions are presented.

|  |  |
| --- | --- |
| C:\Users\tmap8b\Desktop\dsafsaf.jpg | C:\Users\tmap8b\Desktop\fgd.jpg |
|  | C:\Users\tmap8b\Desktop\untitled10.jpg |
| (a) | (b) |

Fig. . Cross-sectional distribution and corresponding frequency distribution of gas holdup for the conditions of (a) reference case of pilot plant-scale spouted beds at z/Dc=1.8 and (b) similar gas holdup radial profile of lab-scale spouted beds at z/Dc=1.8.

***II.B. Fraction of solids cycle time in spout region for gas-solids spouted beds using RPT***

Based on the RPT data for the reference case, similar gas holdup profile, and dissimilar gas holdup profile, we calculated the particle cycle time for solid particles in the spout, annulus, and fountain. To facilitate comparisons of the two scales spouted beds and the studied conditions, these cycle times were nondimensionalized by calculating the contribution of each region's cycle time to the average particle cycle time for each bed under the corresponding studied conditions. In Fig. 6, solids cycle time distributions are shown for reference case, similar gas holdup radial profiles, and dissimilar gas holdup radial profiles (Table 1). There are fewer deviations observed between the two cases when the gas holdup profiles are similar to those of the reference case, indicating that similar gas holdup profiles can lead to similar hydrodynamic behaviour. This suggests that the gas holdup profile has an important influence on the hydrodynamic behaviour of the spouted beds. As a result, it is necessary to consider the gas holdup profile when designing or evaluating the performance of the spoouted beds. Compared to the reference case, the absolute deviation between fractions of time spent in the spout was 5.36% and 18.26% for similar and dissimilar gas holdup profiles. Thus, when the gas holdup profile is similar, the deviation in time spent in the spout is much smaller than when the gas holdup profile is dissimilar. This indicates that the gas holdup profile has a significant impact on the hydrodynamic behaviour of the spouted beds.The absolute relative deviation between the fractions of time spent at the fountain under similar and dissimilar gas holdup profiles was 3.38% and 24.83%, respectively, compared to the reference. As compared to the fraction of time spent in the annulus for the reference case under similar gas holdup profiles, the absolute relative deviation is 0.79%. The absolute relative deviation increased to 4.29% when comparing the fraction of time spent in the annulus between the reference case and the conditions of dissimilar gas holdup profiles. Thus, the gas holdup role in scaling up gas-solids spouted beds is further validated by these findings. Therefore, it is clear that gas holdup plays an important role in scaling up a gas-solids spouted bed. This is evidenced by the difference in the fraction of time spent in all the regions of spouted beds when comparing the reference case to the conditions of dissimilar gas holdup profiles.

|  |
| --- |
|  |
|  |
|  |

Fig. . Distribution of fraction of solids cycle time of each region in the bed for the conditions of Cases (a) reference, (b) similar, and (c) dissimilar gas holdup radial profiles.

***II.C. Implementation of the new scale-up methodology of gas-solids spouted beds.***

It is recommended to implement the new scale-up methodology for gas-solid spouted beds by following the following steps [[8](#_ENREF_8), [9](#_ENREF_9), [20](#_ENREF_20)]: To ensure successful implementation, the steps must be followed in the correct order and with the necessary attention to detail.

I.          Measure the gas holdup profiles at a dimensionless height on the spouted beds that need to be scaled up or down. This is necessary to ensure that the scaled-up spouted beds will have the same gas holdup profiles as the reference spouted beds. This step also helps to ensure that the gas-solid flow patterns in the scaled-up spouted beds will be similar to those in the reference spouted beds, which is important for accurately predicting the flow behavior of the scaled-up spouted beds.

a.      The measurement should include the conical portion of the bed as well as the cylindrical portion including the annulus, spout, and fountain. This helps to replicate the same flow behavior that is seen in the reference spouted beds, which will ensure that the scaled-up version is as accurate as possible. Knowing the exact flow patterns will allow for the best predictions of the scaled-up bed's behavior.

b.      To avoid disturbing the flow, especially in the annulus and the spout-annulus boundary, invasive measurement techniques are not recommended. Instead, non-invasive techniques should be employed to ensure an accurate assessment of the scaled-up bed's behavior. Non-invasive techniques are less disruptive to the flow and can provide more accurate measurements of the scaled-up bed's behavior. Additionally, non-invasive techniques do not require any physical contact with the bed, which eliminates the potential for disruption.

II.          Scaled spouted beds should be searched for similar gas holdup profiles at dimensionless heights to those obtained in the reference case (Step I) using validated computational fluid dynamics (CFD). This is because the gas holdup profile is an important factor in determining the effectiveness of the spouted bed, and CFD can provide a more accurate representation of the gas holdup.

a.      As indicated in the scale-up approach [8], the scaled spouted beds should be geometrically similar to the reference case.  This means that the geometry of the scaled bed should be maintained despite the changes in the dimensions, so that the relative gas holdup profiles are also similar.

b.      When acquiring gas holdup profiles using CFD is difficult or takes time and effort, at least closer gas holdup profiles between the reference case and scaled spouted beds must be obtained. CFD is a valuable tool for obtaining detailed information on the gas holdup profiles of spouted beds, but it is time-consuming and requires a lot of computational power. Therefore, it is important to acquire at least a closer gas holdup profile for comparison between the reference case and the scaled spouted beds.

c.      The closer the radial gas holdup profiles are to the reference case, the better the hydrodynamic similarity. Moreover, precise gas holdup profiles should be ensured to ensure a higher degree of hydrodynamic similarity between the reference case and the scaled spouted beds.

             III.          Develop, build, and operate the newly scaled gas-solids spouted beds under the operating conditions identified in Step II. This step is necessary in order to ensure that the scaled spouted beds are operating under the same conditions as the reference case. This will ensure that the radial gas holdup profiles are as close as possible to the reference case, ensuring a higher degree of hydrodynamic similarity.

             IV.          At the identified operating conditions and at the selected dimensionless height, evaluate the gas holdup radial profiles of the constructed scaled spouted bed. By measuring the radial profiles of the gas holdup, the effectiveness of the scaled spouted bed at the selected dimensionless height and operating conditions can be determined. This is important for understanding the performance of the spouted bed and ensuring that it has been scaled as expected.

In Step IV, non-invasive gamma-ray densitometry (GRD) is recommended. It can be used to measure radial gas holdup profiles and flow regimes at small and large scales non-invasively. GRD has several advantages over other measurement techniques such as high accuracy and repeatability, the ability to measure at multiple depths, and the ability to measure in various flow regimes. Additionally, it is non-invasive, meaning it does not require any physical contact with the fluid being measured, which makes it safer and more cost-effective.

V.          If necessary, refine the operating conditions used in Step III to generate gas holdup profiles that are similar to those of the reference case in Step I. This is done to ensure that the operating conditions used in Step III are optimal for producing the desired gas holdup profile. By refining the operating conditions, it allows for the most accurate comparison between the gas holdup profiles of the reference case and the one generated in Step III.

IV. Conclusions

An advanced non-invasive radioactive particle tracking (RPT) technique and gamma-ray computed tomography (CT) have been used to validate the new scaling-up methodology for gas-solid spouted beds that is based on matching the gas holdup radial profiles between two different sizes of beds. This new methodology has been successfully validated, showing its applicability and reliability for scaling-up of gas-solid spouted beds. A similarity of hydrodynamics was obtained between small and large-scale gas-solid spouted beds when gas holdup profiles were similar. Hydrodynamic similarity was determined based on fractions of cycle time in each region of the beds, radial profiles of gas holdup, and gas-holdup cross-sectional distributions. As a result of dissimilarity in the gas holdup radial profiles between small and large spouted beds, dissimilarities in the aforementioned parameters were found. When the gas holdup radial profiles were different, the fractions of cycle time, gas holdup profiles, and gas-holdup cross-sectional distributions were found to be dissimilar. The agreement between the findings of this study and those reported in the other studies, as well as the evidence that the gas phase dictates the hydrodynamics of the gas-solid spouted bed, indicates that the gas holdup profile has a significant impact on cycle time, gas holdup profiles, and gas-holdup cross-sectional distributions. As such, the CT and RPT results presented here can be used to effectively validate the accuracy of CFD simulations. Furthermore, the new scale-up methodology can be applied by applying computational fluid dynamics (CFD) as an evaluation tool to identify operating conditions that are similar for both small- and large-scale gas-solid spouted beds in terms of gas holdup. By using CFD simulations, it is possible to identify operating conditions that can be used to scale up from a small-scale environment to a larger one, while maintaining the same gas holdup profiles.

**Nomenclature**

|  |
| --- |
| Symbols |
| *dp* | : | particle diameter, m |
| *Dc* | : | inner column diameter, m |
| *Di* | : | inlet orifice diameter, m |
| *Fr* | : | Froude number |
| *g* | : | acceleration of gravity, m s-2 |
| *H* | : | static bed height, m |
| L | : | column length, m |
| *P* | : | bed pressure, Pa |
| ***P*** | : | vector of the cumulative probability distribution of the solids particles penetration into the spout along the spout height. |
| *Re* | : | Reynolds number |
| R | : | column radius, cm |
| r |  | radial position from the axis of the column, cm |
| *r/R* |  | dimensionless radius |
| *T* | : | bed temperature, K |
| $\overbar{T}\_{sp}$, $\overbar{T}\_{an}$, $\overbar{T}\_{fo}$ | : | mean residence time of solids in the spout region, in the annulus region, in the fountain region, respectively, second.  |
| $\overbar{T}\_{cycle}$, | : | mean cycle time of the solids in the spouted beds, second.  |
| t | : | time, second |
| *U* | : | superficial gas velocity, m s-1 |
| *Ums* | : | minimums pouting velocity, m s-1 |
| z | : | axial distance form inlet orifice, m |

|  |
| --- |
| Greek letters |
| *β* | : | fluid-particle interaction coefficient, kg m3 s-1. |
| *ρs* | : | particle density, Kg m-3. |
| *ρf* | : | fluid density, Kg m-3. |
| µ | : | fluid viscosity, Kg m-1 s-1. |
| *ϕs* | : | sphericity of particles. |
| *φ* | : | inertial friction angle of particle, deg. |
| εs | : | solids fraction (or solids holdup). |
| εg | : | gas fraction (or gas holdup). |

References

1. Juhn, P.E., et al., *IAEA activities on passive safety systems and overview of international development.* Nuclear Engineering and Design, 2000. **201**(1): p. 41-59.

2. Miller, G.K., et al., *Calculating failure probabilities for TRISO-coated fuel particles using an integral formulation.* Journal of Nuclear Materials, 2010. **399**(2–3): p. 154-161.

3. Liu, M., Y. Shao, and B. Liu, *Pressure analysis in the fabrication process of TRISO UO2-coated fuel particle.* Nuclear Engineering and Design, 2012. **250**(0): p. 277-283.

4. Pannala, S., et al., *Simulating the Dynamics of Spouted-Bed Nuclear Fuel Coaters.* Chemical Vapor Deposition, 2007. **13**(9): p. 481-490.

5. He, Y.L., C.J. Lim, and J.R. Grace, *Scale-up studies of spouted beds.* Chemical Engineering Science, 1997. **52**(2): p. 329-339.

6. Al-Dahhan, M., et al., *Scale-up and On-line Monitoring of Gas-solid Systems Using Advanced and Non-invasive Measurement Techniques.* Procedia Engineering, 2014. **83**(0): p. 469-476.

7. Aradhya, S., H. Taofeeq, and M. Al-Dahhan, *A new mechanistic scale-up methodology for gas-solid spouted beds.* Chemical Engineering and Processing: Process Intensification, 2016. **110**: p. 146-159.

8. Ali, N., T. Al-Juwaya, and M. Al-Dahhan, *An advanced evaluation of the mechanistic scale-up methodology of gas–solid spouted beds using radioactive particle tracking.* Particuology, 2017. **34**: p. 48-60.

9. Ali, N., T. Aljuwaya, and M. Al-Dahhan, *Evaluating the new mechanistic scale-up methodology of gas-solid spouted beds using gamma ray computed tomography (CT).* Experimental Thermal and Fluid Science, 2019. **104**: p. 186-198.

10. Al Mesfer, M.K., A.J. Sultan, and M.H. Al-Dahhan, *Impacts of dense heat exchanging internals on gas holdup cross-sectional distributions and profiles of bubble column using gamma ray Computed Tomography (CT) for FT synthesis.* Chemical Engineering Journal, 2016. **300**: p. 317-333.

11. Sultan, A.J., L.S. Sabri, and M.H. Al-Dahhan, *Influence of the size of heat exchanging internals on the gas holdup distribution in a bubble column using gamma-ray computed tomography.* Chemical Engineering Science, 2018. **186**: p. 1-25.

12. Al Mesfer, M.K., A.J. Sultan, and M.H. Al-Dahhan, *Study the effect of dense internals on the liquid velocity field and turbulent parameters in bubble column for Fischer–Tropsch (FT) synthesis by using Radioactive Particle Tracking (RPT) technique.* Chemical Engineering Science, 2017. **161**: p. 228-248.

13. Sabri, L.S., A.J. Sultan, and M.H. Al-Dahhan, *Mapping of microalgae culturing via radioactive particle tracking.* Chemical Engineering Science, 2018. **192**: p. 739-758.

14. Sabri, L.S., et al., *A Detailed Hydrodynamic Study of the Split-Plate Airlift Reactor by Using Non-Invasive Gamma-Ray Techniques.* ChemEngineering, 2022. **6**(1): p. 18.

15. Alghamdi, A.A., et al., *GEANT4 Simulation for Radioactive Particle Tracking (RPT) Technique.* Sensors, 2022. **22**(3): p. 1223.

16. Ali, N., T. Al-Juwaya, and M. Al-Dahhan, *An advanced evaluation of spouted beds scale-up for coating TRISO nuclear fuel particles using Radioactive Particle Tracking (RPT).* Experimental Thermal and Fluid Science, 2017. **80**: p. 90-104.

17. Ali, N., T. Al-Juwaya, and M. Al-Dahhan, *Demonstrating the non-similarity in local holdups of spouted beds obtained by CT with scale-up methodology based on dimensionless groups.* Chemical Engineering Research and Design, 2016. **114**: p. 129-141.

18. Al-Juwaya, T., N. Ali, and M. Al-Dahhan, *Investigation of cross-sectional gas-solid distributions in spouted beds using advanced non-invasive gamma-ray computed tomography (CT).* Experimental Thermal and Fluid Science, 2017. **86**: p. 37-53.

19. Al-Juwaya, T., N. Ali, and M. Al-Dahhan, *Investigation of hydrodynamics of binary solids mixture spouted beds using radioactive particle tracking (RPT) technique.* Chemical Engineering Research and Design, 2019. **148**: p. 21-44.

20. Al-Juwaya, T., N. Ali, and M. Al-Dahhan, *Experimental validation of the mechanistic scale-up methodology of gas–solid spouted beds using radioactive particle tracking (RPT).* Annals of Nuclear Energy, 2023. **181**: p. 109559.

21. Mathur, K.B. and P.E. Gishler, *A technique for contacting gases with coarse solid particles.* AIChE Journal, 1955. **1**(2): p. 157-164.