

Study on Sedimentation Characteristics of Core Debris in Severe Accident of Sodium-cooled Reactor

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Study on Sedimentation Characteristics of Core Debris in Severe Accident of Sodium-cooled Reactor

by

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Chapter 1

GENERAL INTRODUCTION

1.1 Nuclear power development

It is human nature to test, to observe, and to dream. The history of nuclear energy is the story of a centuries-old dream becoming a reality. Sustainable energy security is one of the prime requirements for the advancement of civilization. Global population growth in combination with industrial development and increasing standards of living day by day causes strong energy demand. This imposes great pressure to every nation in the world. The energy security depends upon a diverse mix of energy sources that balances cost, availability and environmental impact. Nuclear energy provides reliable, low-cost base load electricity as well as the ability of producing electricity without greenhouse gas emissions make it gradually stand out from all the energy sources since 1942. The development of the first self-sustaining nuclear chain reaction on December 2, 1942, led by Enrico Fermi at the University of Chicago was the first man made reactor, known as Chicago pile-1 (Joseph, 2004). The world stepped on the nuclear age. One of the most important uses of nuclear energy is the production of electricity. Nuclear power plants are the most reliable sources of electricity production, measured by the capacity factor (i.e., the percentage of electricity actually produced in comparison to the total potential electricity that the plant is capable of producing). The average capacity factor of the nuclear plants is approximately 90 percent, compared to 68 percent for coal.

The 1950s has seen the start of the penetration of nuclear power into the electricity market. It was a period of great enthusiasm, intensive research and development (Char, 1987). A major goal of nuclear research in the mid of 1950s was

to show that nuclear energy could produce electricity for commercial use. Electricity was generated for the first time by a nuclear reactor on December 20, 1951, at the first Experimental Breeder Reactor (EBR-I) near Arco, Idaho, which initially produced about 100 kW (Michal, 2001). The world's first commercial nuclear power station: Calder in Sellafield (England) began its operation in 1956 with an initial capacity of 50 MW (later 200 MW) (Helge, 1999). The subsequent commercial production of the nuclear power has become the most important source for electricity in some countries.

During the 1960s nuclear power achieved the status of a technically proven as well as economically and commercially viable energy source (Char, 1987). Installed nuclear capacity initially rose relatively quickly, rising from less than 1 gigawatt (GW) in 1960 to 100 GW in the late 1970s, and 300 GW in the late 1980s (Fischer, 1997). The oil price shocks at the beginning of the 1970s gave a big boost to the promotion and further development of nuclear power in several countries (such as Germany, Canada and Japan). Subsequently, some other countries like Mexico, Brazil Taiwan and South Korea took effective preparation to initiate their nuclear programs. In the subsequent years three severe accidents had occurred, which include the Three Mile Island accident (1979), the Chernobyl disaster (1986) and Fukushima Daiichi accident (2011). Once again nuclear power was to receive a cruel blow. This, in turn, had a negative influence on the overall trend of expanding the use of nuclear power. A general movement against nuclear power arose during the last third of the 20th century, based on the fear of a possible nuclear accident as well as the history of the accidental release of radiation and the history of radiation hazard to public, nuclear proliferation, and on the opposition to nuclear waste production, transport and lack of any ultimate storage plans (Cohen, 1990). More than two-thirds

of all nuclear plants ordered after January 1970 were eventually cancelled (Fischer, 1997). By the end of the 1970s it became clear that nuclear power would not grow nearly as dramatically as once believed. Following the Fukushima Daiichi nuclear accidents, the international Energy Agency halved its estimate of additional nuclear generating capacity to be built by 2035. Germany decided to close all its reactors by 2022, and Italy has banned nuclear power (from Nuclear power at Wikipedia, 2013). Nuclear power has become a controversial issue causing a debate on its possible future expansion. Public acceptance became a major issue for the promoters of nuclear power (Char, 1987). This reasonably grounds a recession in the nuclear industry. However, the impact of these three accidents was not just negative. The lessons learned undoubtedly spurred the research on nuclear safety for the further improvements in the design, construction, and operation of nuclear plants to achieve better reliability.

The electricity demand is increasing twice as fast as overall energy use and is likely to rise at least 73% to 2035 (from World energy needs and nuclear power at WNA, 2013). The world marketed energy consumption is projected to increase by 56% from 2010 to 2030 as presented in the International Energy Outlook 2013, reported by the US Energy Information Administration (EIA) (DOE/EIA-0484, 2013). The rising energy demand resulted from the booming economy, on-going urbanisation, increasing standards of living for many people in developing countries will strongly require increased energy supply. Over 70% of the increased energy demand is from developing countries, led by China and India (from World energy needs and nuclear power at WNA, 2013). The greatly increased energy demand essentially emphasizes to re-evaluate the structure of energy supply. The current largest sources of energy are the combination of coal, oil and natural gas. They will

last quite a while but will probably run out or become harmful for environments in tens to hundreds of years (Galperin, 1992). Growing concern about the effects of greenhouse gases on global warming and climate change has raised peoples' awareness on reduced use of fossil fuels instead of low-emission sources of energy such as nuclear power, wind power and solar energy. Although wind power can be a good source of clean energy, however, the capacity factor of the wind power is only 30-40%, which strongly depends on whether enough wind is blowing to turn turbines at the necessary speeds. Solar power can also be a potential source of clean energy but is not much developed except for special applications because of its high cost. Currently, demonstration on electricity generation has identified the wind power, solar energy and other "renewable" sources as an uneconomic option for base-load power. The potential candidate of the renewable energy can be the Fusion power which could solve many of the difficulties of fission power. Fusion powered electricity generation was initially believed to be readily achievable, as fission power had been. The first plasma is expected to be produced in 2016 by the International Thermonuclear Experimental Reactor (ITER). The subsequent step after ITER is called DEMCO, a demonstration reactor. DEMCO should come into operation 30-35 years after the start up of ITEAR (from The ITER project, 2013). However, there are still significant barriers standing between current scientific understanding and technological capabilities for the realistic realization of fusion as an energy source. In fact, commercial power production is still believed to be unlikely before 2050 although intense theoretical and experimental investigation was started in the 1950s.

Of the known and proven energy technologies, nuclear power is the only readily available large-scale alternative to renewable and fossil fuels for production of continuous, reliable supply of electricity in the most environmentally benign way

(Cohen, 1990). Nuclear energy is a stabilizing factor in deregulated electricity markets because it is not affected by the price volatility experienced by other major energy sources, such as coal, oil and natural gas. Consequently, nowadays many nations are considering an expanded role for nuclear power in their energy portfolios.

The high projection for the nuclear capacity in 2030 is 800 GW (IAEA, 2010). To refer to the possible nuclear power industry revival, driven by rising fossil fuel prices and new concerns about meeting greenhouse gas emission limits, the term “nuclear renaissance” has been used since about 2001 (from Nuclear power at Wikipedia, 2013). However, new reactors under construction in Finland and France, which were meant to lead a nuclear renaissance, have been delayed and are running over-budget (from Nuclear power at Wikipedia, 2013). China has 25 new reactors under construction and there are also a considerable number of new reactors being built in South Korea, India, and Russia. In the USA, two new Generation III reactors are under construction at Vogtle. US nuclear industry officials expect five new reactors to enter service by 2020, all at existing plants. Canadian uranium-mining company Cameco expects the size of world’s fleet of operating reactors in 2020 to increase by 90 reactors, 10% less than before the Fukushima accident. As of November 2013, there are 435 nuclear power reactors in operation with a total net installed capacity of 371.33 GW (e) in the world, operating in 31 countries (from Nuclear power at Wikipedia and IAEA’s database on nuclear power reactor, 2013). Nuclear power generation is an established part of the world’s electricity mix providing some 11% of world’s electricity (from World energy needs and nuclear power at WNA, 2013). The forthcoming booming period of nuclear power development is expecting together with the under way construction of another 70 reactors in 14 countries (IAEA’s database on nuclear power reactor, 2013).

However, the nuclear emergencies at Japan's Fukushima Daiichi nuclear power plant and other nuclear facilities raised questions over the future of the renaissance.

Current thermal reactors make relatively inefficient use of nuclear fuel, fissioning only the very rare uranium-235 isotope. From the onset, nuclear scientists understood that today's reactors fuelled essentially with uranium-235 exploited less than one percent of the energy potentially available from uranium (from Fast neutron reactor at WNA, 2013). As opposed to current thermal reactors, breeder technology has been used in several reactors. In this perspective, presently there is renewed interest all over the world in the development of fast reactor technology. It has been estimated that there is up to five billion years' worth of uranium-238 for use in the fast breeder reactors. Therefore, many nations in the world believe that the development and deployment of advanced nuclear reactors based on first neutron fission technology is important to ensure the sustainability, reliability, and security of the world's long-term energy supply. The essence of the fast reactor exhibits its ability to generate new fissile fuel in larger extent than it consumes when begins generating electricity. In the fast reactors fertile material breeds up into fissile, so it is called fast breeder reactor (FBR). The R&D programs of the fast reactor development technology were vigorously started since the early 1950s, eventually leading the construction and operation of experimental and prototype reactors. The first operational fast reactor was Clementine, built in 1946 at Los Alamos in USA (Walter, 1981). EBR-I was the pioneer fast reactor of producing nuclear electricity on December 20, 1951 at Idaha Falls in USA. Thereafter, the fast reactor development program in USSR (BR-1), UK (DFR), and France (Rapsodie) was initiated to build their own experimental fast reactor facility (Walter, 1981). Sequentially, the fast reactor development program in Germany (KNK), Japan

(JOYO) and China (CEFR) was launched in the 1960s, 1967s, and 1970, respectively to achieve their competence with the future course of advanced development.

Several countries have research and development programs for improved Fast breeder reactor. In this context, the experimental reactors, namely Phénix (France), SNR (Germany), MONJU (Japan), PFR (UK), CRBR (USA), BN-350 and BN-600 (USSR) were operating mainly as R&D tools (i.e., irradiation facilities) to implement the operational experience for the development of commercial size prototype fast reactor. Today there has been progress on the technical front to breed and use plutonium, however, the economics of fast reactors still depends on the value of this fuel relative to the cost of fresh uranium (from Fast neutron reactors at WNA, 2013). Recent geological exploration showed that scarcity was not going to be a concern for some time as it was thought. In addition, significant technical and material problems were encountered with FBRs. All these factors might have an influence on the shut down process of some fast reactors which mostly include Superphénix (France), KNK-II (Germany), PFR (UK), BN-350 (Kazakhstan), FFTF and BR-II (USA). However, in some countries, particularly in Russia, China and India, the development of fast reactor is in the ascendant or assigned high priority. Russia plans to expand the nation's use of breeder reactors with the BN-800 reactor, scheduled to become operational in 2014. (from Sodium coolant arrives at Beloyarsk at WNN, 2013). Both China and India are building breeder reactors. The China Experimental Fast Reactor began producing power in 2011. The Indian 500 MWe Prototype Fast Breeder Reactor scheduled to become operational in 2014, with plants to build five more by 2020. Other countries such as France and Japan greatly emphasize on the fast reactor development program considering the prospect of

using uranium resources more efficiently. A significant portion of Japanese energy policy has been devoted since 1967 for the development of FBRs in an effort to dramatically improve uranium utilization.

Several generations of nuclear reactors are commonly distinguished. More specifically, three generations of commercial nuclear power plants have been evolved over the last decades after the early beginning of nuclear energy in the 1940s. Generation I reactors were developed in the 1950s – 60s in the early prototype reactors. Generation II reactors were emerged in the 1970s – 80s, constituting most of presently working commercial reactors (Comsan, 2007). Generation III reactor is an advanced stage of design of the generation II nuclear reactors. In generation III reactors, improvements of designs started in late 1980s by incorporating passive or inherent safety systems. The first Generation III reactor began its operation in 1996 at Kashiwazaki in Japan. The so-called Generation III+ reactors are under way, which offers significant improvements in safety and economics over Generation III advanced reactor designs certified by the NRC in the 1990s (from Generation III reactor at Wikipedia, 2013). The plants to be built newly from now until 2030 will likely be chosen from these plants of type Generation III+. Generation IV is expected to be available beyond 2030 which is at conception stage under international joint effort of renewed R&D (Comsan, 2007).

1.2 Global programs on fast reactors and Generation IV systems

The expedition of long term development of nuclear power as a part of the world's future energy mix generally recognize the development of fast reactor technology with closed fuel cycle (from Nuclear power at IAEA official website, 2013). The fast breeder reactor (FBR) is a promising source of producing electricity

with breeding additional fissile material for the future fuel stocks, will be needed when economic uranium supplies for the advanced LWRs or other thermal options diminish. The FBRs are versatile and flexible technology that promises to breed more fuel by converting nuclear waste into fissile material. The FBR technology has the potential to make the production of energy from uranium 100 times more efficient than with the existing thermal reactor, reducing the amount and toxicity of radioactive waste. (from Fast reactors at IAEA official website, 2013). FBR technology was developed in the 1960s with demonstration and prototype reactors operating in a number of countries including China, France, Germany, India, Japan, the Russian Federation, the United Kingdom and the United States. Currently, FBRs are selected as important parts of the Generation IV (Gen IV) reactors.

To advance nuclear energy with a view to meet future energy needs, some countries such as Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom and the United States have agreed on a framework for international cooperation in research for a future generation of nuclear energy systems, known as Generation IV. The Gen IV nuclear energy systems (Gen IV systems) are innovative reactors that will comply with the concept of sustainable development to meet the energy needs in the future with optimizing management of nuclear waste (from GIF symposium proceedings, Annual report 2012). Research into these reactor types was officially started by the Generation IV International Forum (GIF) to lead the collaborative efforts of the world's leading nuclear technology nations. In December 2002, a technology roadmap was published by the GIF member countries (GIF-002-00, 2002). Based on this technology road map, six promising reactor system and fuel cycle concepts have been identified, along with the research required to study the concepts in view of

potential deployment and /or commercialization. The design concepts of three among six Gen IV systems are fast reactors cooled by sodium, lead (lead-bismuth or helium). A fourth, superficial water reactor, includes an option to use fast neutrons and only two operate with thermal neutrons like today's plants. Depending on their respective degrees of technical maturity, the Gen IV systems are expected to become available for commercial introduction in the period between 2015 and 2030 or beyond (from GIF and Generation IV, 2013).

The goals adopted by GIF provided the basis for identifying and selecting six nuclear energy systems for further development. All Gen IV systems have features aiming at performance improvement, new applications of nuclear energy, and/or more sustainable approaches to the management of nuclear materials. Eight technology goals have been ascertained for Gen IV systems in four broad areas: sustainability, economics, safety and reliability, and proliferation resistance and physical system (from GIF and Generation IV, 2013). Sustainability goals focus on fuel utilization and waste management. Enhanced sustainability is achieved primarily through adoption of a closed fuel cycle with reprocessing and recycling of plutonium, uranium and minor actinides using fast reactors; this approach provides significant reduction in waste generation and uranium resource requirements. Economics goals focus on competitive life cycle and energy production costs and financial risk. Safety and reliability goals focus on safe and reliable operation, improvement accident management and minimization of consequences, investment protection, and essentially eliminating the technical need for off-site emergency response. The proliferation resistance and physical protection goal focuses on controlling and securing nuclear material and nuclear facilities (GIF-002-00, 2002). These ambitious goals are shared by a large number of countries as they aim at responding to

economic, environmental and social requirements of the 21st century. They establish a framework and identify concrete targets for focusing GIF R&D efforts for Gen IV nuclear energy systems. The main characteristics of the six Gen IV systems are summarized in the following **Table 1-1** (from GIF and Generation IV, 2013).

Table 1-1 Main characteristics of the Generation IV reactor systems

Generation IV reactor system	Acronym	Neutron	Temperature (°C)	Coolant
Sodium-cooled fast reactor	SFR	Fast	550	Sodium
Lead-cooled fast reactor	LFR	Fast	480-800	Lead
Gas-cooled fast reactor	GFR	Fast	850	Helium
Molten-salt reactor	MSR	Epi-thermal	700-800	Fluoride salt
Supercritical-water cooled reactor	SCWR	Thermal, Fast	510-625	Water
Very-high-temperature reactor	VHTR	Thermal	900-1000	Helium

In particular, four of the systems with high core outlet temperature range 510 °C to 1000 °C offers the possibility for thermo-chemical hydrogen production in contrast of 330 °C of today's LWRs. The Gen IV systems should also offer a true potential for new applications compatible with an expanded use of energy, in particular synthetic hydrogen production, sea-water desalination and process heat production. Nevertheless, the recognition of these objectives should be on the basis of an internationally shared R&D program, which allows wide and official sharing with a large number of countries in a view to avoid any early or premature down selection.

1.3 Liquid metal-cooled fast breeder reactors

Fast breeder reactor (FBR) development is now concentrated on the liquid metal-cooled breeder reactor (LMFBR). This type of reactor is still a very high competitive choice as the next generation nuclear energy system, already been indicated by the outline of the Gen IV roadmap (GIF-002-00, 2002). The LMFBR is an advanced type of nuclear reactor where the primary coolant is a liquid metal. In practice, all LMFBR are fast neutron reactors, and to date most of the fast neutron reactors have been liquid metal-cooled FBRs. Some countries like France, Russia, India, China and Japan assigned a high priority for the development of FBR. For instance, recently France has adopted a policy to replace half of the present nuclear capacity by fast neutron reactors by 2050. (from Fast neutron reactors at WNA, 2013). However, this optimistic outlook is only one side of the picture. Presently, the commercial deployment of LMFBRs is not expected to proceed as rapidly during the 1980s and 1990s was envisaged 10 or 15 years ago. In some countries even the construction of reactor faces difficulties due to political, financial, licensing, and other problems (Khodarev, 2014).

Fast reactors typically use liquid metal as primary coolant. There are various options of liquid metals for the LMFBRs such as Sodium, NaK (a sodium-potassium alloy), Mercury, Lead, Lead-bismuth eutectic, and Tin (from Liquid metal-cooled reactor at Wikipedia, 2013). Some early LMFBRs used mercury, and other experimental reactors have used lead and NaK as the primary coolant, to transfer heat from the core to produce steam, essentially used to power the electricity generating turbines. These coolant options have an advantageous property of being liquid state at room temperature, which is convenient for the experimental rigs but less important for pilot or full scale power stations (from Fast breeder-definition at

Wordiq.com). Sodium is selected as the normal liquid metal coolant for the large power fast breeders since it can remove heat effectively from the compact reactor core and remains in the liquid state over a fairly broad temperature range (Khodarev, 2014). The experience from about 200 reactor-years of experimental and mid-size LMFBR power units has demonstrated that sodium-cooled fast reactors are reliable, as easy to operate as current light-water reactors (LWRs), require straightforward maintenance with relatively low personnel dose generation and handling (Golan, 1989). As of 2013, all large-scale FBR power stations have been liquid metal fast breeder reactors cooled by liquid sodium.

The core of a fast reactor is much smaller than that of a normal nuclear reactor, and it has a higher power density, requiring very efficient heat transfer (from Fast neutron reactors at WNA, 2013). The core configuration of a typical FBR can be distinguished into two parts: inner part and outer part. The inner part of the core essentially consists of fuel rods, which contains a mixture of uranium and plutonium dioxide. Fission reactions dominate in the inner part, while conversion of U-238 to Pu-239 is the predominant process in the outer part. In an FBR this process can be optimized so that it “breeds” fuel, though reprocessing of the blanket material is required to recover it. In such a reactor one can achieve a situation where more fissile plutonium nuclei are produced in a unit time than the number of fissile nuclei which undergo fission. Hence, FBRs can utilize uranium at least 60-times more efficiently than a normal reactor. This has led the spotlight on sodium-cooled fast reactors (SFR) in the Generation IV International Forum (GIF). The sodium-cooled fast reactor is one of the Gen IV reactor projects to design an advanced FBR. The efficient burning capacity of transuranic materials, including degraded plutonium, and the excellent neutron economy are some of the advantages of the SFR, which

enable the utilization of nuclear energy as a sustainable energy source over a very long time period of more than thousands of years (Icimiya, 2007). The conventional SFR of current design uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. The reactor can be arranged in a pool layout or a compact loop layout. Reactor size options under consideration range from small (50 to 300 MW) modular reactors to larger reactors (up to 1500 MW). The two primary fuel recycle technology options are advanced aqueous and pyrometallurgical processing. A variety of fuel options are being considered for the SFR, with mixed oxide preferred for advanced aqueous recycle and mixed metal alloy preferred for pyrometallurgical processing. Owing to the significant past experience accumulated with sodium cooled reactors in several countries, the deployment availability of SFR systems is targeted for 2020 (from GIF and Generation IV, 2013).

1.4 Safety analysis and core disruptive accidents of LMFBR

There are several objectives of the power reactor safety aspects: protection of the plant against damage; protection of the public; and the presentation of evidence of safety. In order to achieve the successful deployment of fast reactors, the safety enhancement is the most important issue to be established. Nuclear reactors are generally designed according to the defence in depth (DiD) safety principle. For the existing FBRs the safety designs and assessments have been carried out from the early stage of their development, by taking into account the prevention and mitigation of the severe accidents on the same basis as the IAEA's current DiD principles (Nakai, 2009). However, the risk from CDAs has been one of the safety concerns in the history of the fast reactors safety evaluation. The necessary condition for successful fast reactor deployment is the understanding and assessment of

innovative technological and design options, based on both past knowledge and experience, as well as on on-going research technology development efforts.

The fast reactor research and technology development programs started in a number of countries in the 1940s and early 1950s. The world's first commercial LMFBR in the USA, a 94 MWe Unit 1 at Enrico Fermi Nuclear Generating Station, went into operation in 1963. It operated for only three years before a coolant problem caused overheating and suffered a partial melt down in 1966, which was finally decommissioned in 1975 (from Fast neutron reactors at WNA, 2013). Since then, Japan and France started their ambitious plans on FBRs. In Japan, JOYO experimental fast reactor which has been operating since its first criticality in 1977 has been boosted to 140 MWt, but has been shut down since 2007 due to damage. The 280 MWe MONJU demonstration FBR at Tsuruga started up in April 1994, but a sodium leakage in its secondary heat transfer system during performance tests in 1995 necessitated its shut down for almost 15 years. The facility was restarted in May 2010 and another accident in August 2010 caused its shut down again (from Fast neutron reactors at WNA, 2013). The Monju sodium leakage accident partially caused an eventual push out of the FBR commercial timeline once to 2030 in 1994, and again to around 2050 in 2005 although there was a strong commitment to FBRs from 1961 to 1994 in Japan (from Fast neutron reactors at WNA, 2013). On the other hand, France operated its first prototype Phénix fast reactor (233 MWe) since 1973 and was dismantled in 2009 because of numerous sodium leaks and fires and a series of potentially serious reactivity incidents. The second large-scale French commercial prototype fast reactor Superphénix (1250 MWe) commenced its operation in 1986, although the plant was closed in September 1998 on the ground of economic and political reasons (Schneider, 2009). In fact, from the beginning of the operation, lots

of trouble encountered with the Superphénix in its everyday operation. This eventually raised the public concern about the safety aspects of nuclear reactors, especially FBRs. The Russian scientists started fast reactor programs from the early 1950s with BR-1, BR-2, BR-5, and BR-10 and subsequently BN-350, BN-600, BN-800, BN-1600 designs were developed. The BN-350 experienced a major sodium fire due to the failure of one of the steam generators. The experience acquired during the initial period of BN-350 operation was used to make changes to the BN-600 design, which was also suffered repeated sodium leaks and fires (Cochran, 2010). More largely, international experience indicates that FBRs are not ready for early commercial use and emphasis on its safety enhancement as the most important issue for the commercial deployment. Therefore, the plan of FBRs commercialization target has slipped from the 1980s to the 2050s.

The operational history of FBRs in Japan, France and other countries clearly indicates that the public acceptance is of prime importance to the commercial deployment of fast reactors. It has already been exemplified that the Three Mile Island accident, the Chernobyl accident and the Fukushima Daiichi accidents have provoked the public concern against the acceptance of nuclear reactor. Although an accident involving a small part of the system, however, its severity can hamper the ultimate fate of the nuclear power projects. This is because such accidents widely affect public opinions in favour of the nuclear power, even spreading out national territory. Although public already accept the advantages of nuclear energy, however, to enhance the public acceptance further for nuclear reactor, especially FBRs, the only barrier is the safety. In the light of this situation, considerable attention should be given for the development of sustainable safety systems as a key essence of the safety improvement.

The classification of nuclear and radiological accidents and the related safety conditions are essentially associated to a particular event in connection to the operation of nuclear facilities. It should be standardized and consistent from one country to another. With regard to this, International Nuclear and Radiological Event Scale (INES) was introduced by the IAEA and the Nuclear Energy Agency of the Organization for Economic Corporation and Development in 1990 in order to enable prompt communication of safety significance information in case of nuclear accidents (INES User's Manual, 2008).

In the INES events are classified at seven levels. Events which are classified in levels 4-7, have greater safety significance and termed "accidents". Events of lesser safety significance are classified in levels 1-3 and termed "incidents". Events which have no safety significance (level 0 or below scale) are termed "deviations" and events which have no safety relevance are termed "out of scale". The lower levels consist of anomalies, incidents and serious incidents. The upper levels are consisted of accidents without significant off-site risk, accidents with off-site risk, serious accidents and major accidents. Each level on the scale is determined by the highest of three scores: off-site effects, on-site effects and defence in depth degradation. The structure of the INES is shown in **Fig. 1-1** (from International Nuclear Event Scale at Wikipedia, 2013). Events are considered in terms of their impact on three different areas: impact on people and the environment; impact on radiological barriers and controls at facilities; and impact on defence in depth. INES is intended to be applicable to all radiological events and all nuclear or radiation safety events, the vast majority of which relate to failures in equipment or procedures.

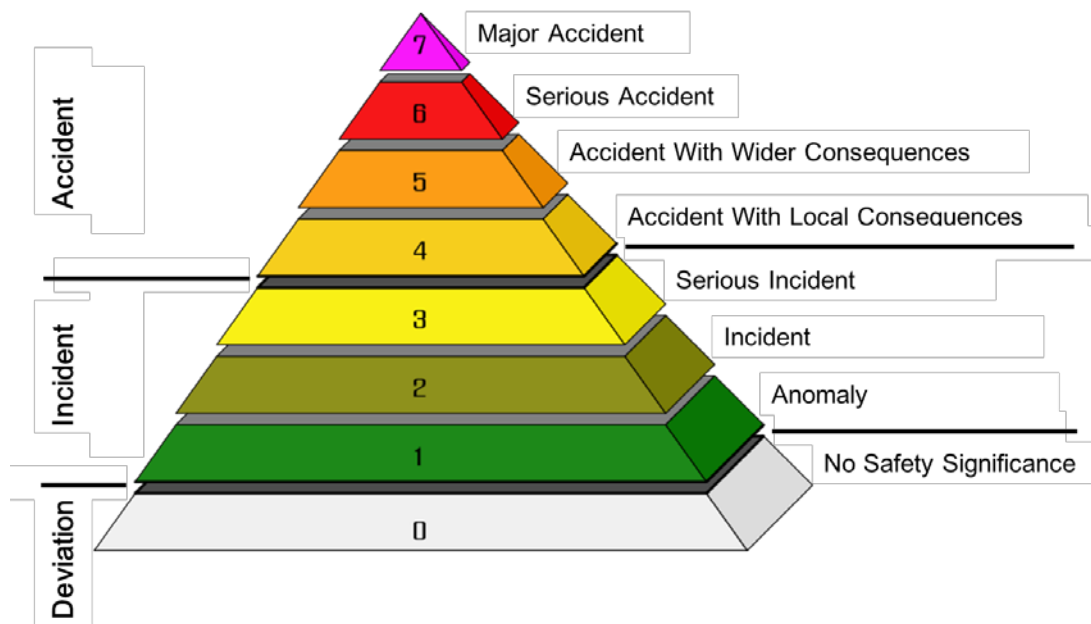


Fig. 1-1 Events classification based on the INES.

Each increasing level of INES presents an accident ten times more severe than the previous levels. One of the key considerations in developing INES rating criteria was to ensure that the significance level of less severe and more localized events would be clearly separated from the very severe accident. Thus the 1979 accident at the Three Mile Island nuclear power plant is rated at Level 5 on INES, and an event resulting in a single death from radiation is rated at Level 4. The 1986 accident at the Chernobyl nuclear power plant is rated at Level 7 on INES. It had widespread impact on people and the environment (INES User's Manual, 2008). In 2011 a severe accident was occurred at the Fukushima daiichi nuclear power plants in Japan due to large scale earthquake followed by tsunami with subsequent release of radioactive materials. INES rating for this disaster was initially declared as Level 4 by Japan's nuclear safety agency. Until March 18, 2011 there had no official rating from the IAEA, but Japanese officials revised the initial assessment of unit-1 to level 5 and gave the same rating to unit-2 and 3. In April 12, 2011 the Fukushima crisis was updated to the INES Level 7 by the IAEA (from Fukushima nuclear accident update log at IAEA's news center website, 2013).

Some early concern about fast reactor safety arose in 1955 after an experiment resulted in a partial meltdown of the MARK-II core in EBR-1. The positive Doppler coefficient of fissile material had a significant effect and was responsible for the positive temperature coefficient of EBR-1, which led to meltdown of the core (Hummel, 1986). Usually, in this type of accident, positive reactivity will be introduced into the core. Thus, if the core disruption cannot be avoided, the accident enters into the transition phase, characterized by the progression of core melting and recriticalities due to fuel compaction. Since a fast reactor core with uranium-plutonium fuel is not in its most reactive configuration under operating conditions, redistribution of the core materials (fuel, steel, sodium) during a core disruptive accident (CDA) may lead to recriticalities and as a consequence to severe nuclear power excursions (Vezzoni, 2012). Therefore, recriticality is a crucial issue in the transition phase. Key questions are whether in this transition sufficient fuel will be ejected from the core to preclude recriticality, and if such reassembly does occur whether it could lead to unacceptably high energy release (Hummel, 1986). So Core Disruptive Accidents still have to be analysed anyway as part of a licensing process (GIF-017-00, 2002). Japan is placing significant emphasis on its recriticality free proposal (Sawada, 2000) and seeks to assure through design features that no compaction-driven recriticality can occur even with low probability events beyond the design base (GIF-005-00, 2002). However, the extensive design effort for accident prevention, including advanced passive safety features, will make the occurrence of such an event extremely unlikely in future LMR development. The significance of severe accidents is still emphasized from the viewpoint of safety design and evaluation to mitigate and accommodate the consequences appropriately

so as to minimize the risk to the public. In this standpoint, investigation of CDAs is crucial in the safety analysis of LMRs.

1.5 Background and objective of the present study

The severe damage caused at the Fukushima Daiichi nuclear plant in Japan resulted from a beyond-design-basis-magnitude of natural disaster, combining an earthquake and a tsunami on March 11, 2011 has raised the rationality of the safety concern in CDA (Mori, 2012). This disaster creates concern among worldwide public to comprehend the occurrence of severe accidents including the CDAs, even if their probability is extremely low. The Fukushima Daiichi accident revealed the subsequent formation of corium either for an absolute or delayed deficiency of cooling of the reactor core. To ensure the safety margin of the in-vessel retention, assurance of adequate cooling and stabilization of the corium is prerequisite (Park, 2013). After such a CDA in SFR, melt-sodium contact is expected to lead solidification and fragmentation with small particles (Tentner, 2010). As a consequence, in the course of melt relocation, fragmented debris can form debris beds on core-support structure and/or in the lower plenum of the reactor vessel (Zhang, 2008). **Fig.1-2** shows the outline of material relocation phase toward forming the debris bed (Tobita, 2013). Such debris bed is formed with particles of different sizes and varying porosity (Harvey, 2008). The debris tray presented in Fig. 1-2, is one of the design concepts of in-vessel retention (IVR) in a CDA caused by anticipated transient without scram (ATWS), proposed for the Japan sodium-cooled fast reactor (JSFR). The ATWS type CDA mostly initiates due to the unprotected loss of flow (ULOF), unprotected transient over power (UTOP) and unprotected loss of heat sink (ULOHS). The importance of ULOF in terms of its frequency is much

greater than those of UTOP and ULOHS. Based on the design characteristics of JSFR, ULOF was selected as the representative CDA for JSFR (Sato, 2011). The ULOF scenario aimed at by the JSFR design to obtain in-vessel retention of the degraded core material during post-accident material relocation (PAMR) phase. Therefore, assessment of the dynamics of molten fuel relocation following such CDAs in JSFR is of importance in studies of accident energetic in the PAMR phase. The prospective for safe containment of the core materials following a CDA depends to a great extent on the post-accident distribution of fuel and other core materials (Chun, 1980). In addition, the post-accident heat removal (PAHR) for JSFR is designed to prevent the debris bed from reaching the limit conditions for a coolable debris bed. The basic idea that underlies the PAHR design is to broaden the fuel debris bed as much as possible inside the reactor vessel (Tentner, 2010). In the JSFR design, it is intended to allow effective quenching of the molten-core materials with a subsequent widespread debris distribution onto the multi-layer debris tray (Sato, 2011), as presented in Fig. 1-2.

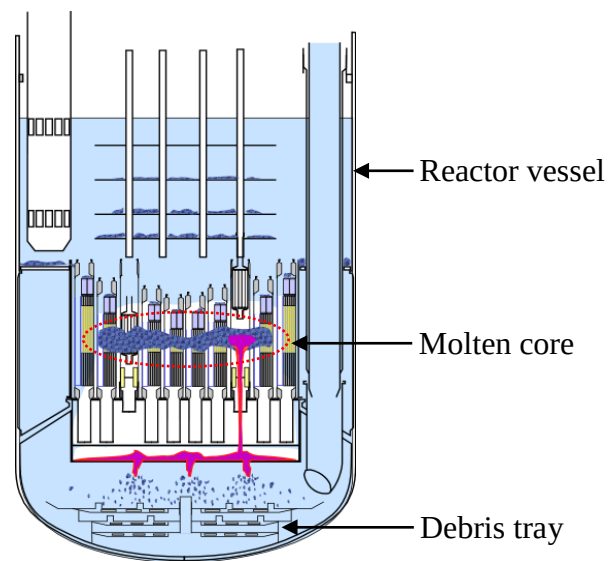


Fig. 1-2 Outline of material relocation phase in CDA.

It is a critical issue to explore the debris bed configuration, which will ensure the self-sustainable long-term cooling mechanism of the debris bed (Park, 2013). At accident transients, the core melt will likely to pour down into the lower sodium plenum, leading to quenching with complete fragmentation of the melt jet (Bachrata, 2014). The current mitigation scenarios at Gen IV type SFR assumed that if the molten fuel/steel mixture in the core cannot be contained in a coolable configuration, it will relocate to the in-vessel core catcher (Bachrata, 2014). Thus, the investigation of debris bed formation characteristic during debris sedimentation onto the debris tray is another important point from recriticality concern and cooling considerations of JSFR in order to ensure the safety margin of IVR in CDAs (Sudha, 2011). **Fig. 1-3** shows a schematic view of this kind of debris bed formation process onto the debris tray of JSFR for the core melt discharge through control rod guide tube (CRGT) in PAMR phase (Tobita, 2013).

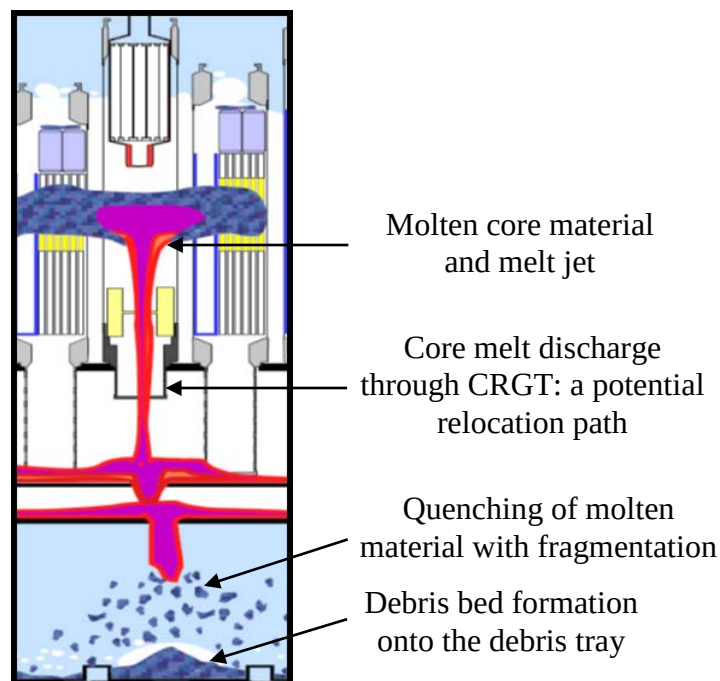


Fig. 1-3 Schematic view of debris bed formation process onto the debris tray.

Under a very low probable CDA scenario of SFR, the physical status of debris generated during the molten fuel interactions with coolant plays a crucial role for the post accidental decay heat removal (Harvey, 2008). The heat transfer phenomena in the debris bed have gained much attention in last decades. Lots of theoretical and experimental investigations have been focused on the related subjects of debris bed characteristics (Harvey, 2008, Yakush, 2009, Weimin, 2007). However, among most of those researchers, the shape of debris bed was specified ad-hoc, e.g., a cylinder (Burger, 2006), cone or Gaussian-shaped heap (Yakush, 2008), heap-like (Karbojian, 2009, Weimin, 2010), conical shape (Zhang, 2010) and homothetic pile (Alvarez, 1982). Moreover, previous analysis of debris bed coolability in a reactor accident has generally assumed that debris beds are homogeneously and uniformly spreading over pool bottom (Weimin, 2007). However, to find out the configuration of a realistic debris bed shape for a particular scenario of melt release, the process of debris bed formation has to be clarified taking into account the sedimentation process of the debris particles. In a view to get inside of the sedimentation features, batch experimentation can be a useful method to mechanistically investigate debris bed formation characteristic at laboratory scale. Batch sedimentation is an important process with many practical applications in chemical, mining, and civil engineering as well as nuclear reactors following a CDA when the coolability and recriticality of the core debris are a major concern (El-genk, 1984). During CDA involving core melting or disruption, highly enriched fuel particles or melt globules may be dispersed into the reactor coolant system or relocate downwards to challenge the reactor structural integrity (Kim, 1985). If such CDA was to occur in SFR, the melt will enter into the sodium gradually, leading to complete fragmentation with small particles, subsequently forming a debris bed in the lower plenum (Tentner, 2010). In

the event of a CDA, melt relocation through the potential accessible paths can mainly be initiated due to the gravity-driven discharge of molten core materials. Study of melt-debris relocation and bed formation characteristic is important to analyse coolability and the potential risk of recriticality, because inadequate cooling could cause a section of the bed to reach a temperature high enough to melt the particles and to thermally attack the supporting structures of stainless steel, which has relatively low melting point. The potential recriticality would be mitigated if sufficient molten fuel (~40%) can be rapidly relocated away from the reactor core region through some relocation paths and reconfigured within the lower plenum region (Spencer, 1979 and Sienicki, 1985). If the molten core materials relocated from the core cannot be contained in a coolable configuration in the lower plenum, it could eventually make its way to the lower head of the reactor vessel, causing a potential melt through of the reactor vessel (Tentner, 2010). Formation of coolable debris bed after complete fragmentation and quenching of molten fuel in sodium pool can potentially ensure the in-vessel retention (Tobita, 2013).

To estimate the safety margin of in-vessel retention of molten material in CDA it is necessary to study the debris bed characteristics in regard to clarify its cooling mechanism. Owing to the significance of the debris bed characteristics on its coolability aspects, it is imperative to perform particle sedimentation experiments with simulant materials to develop a fundamental database on the particle bed formation process. In addition, investigation of the particle bed shape under different sedimentation behaviour is crucial to mitigate the recriticality concern of the accumulated core melts on the debris tray for the safe retention and stabilization of the whole core debris within the lower plenum. From this view point, the present experimental data can be useful for the effective design of the debris tray by taking

into account the particle bed shape in a similar fashion as observed in the present experiments. This is because the efficiency of the debris tray depends on multiple phenomena, including debris bed formation and cooling process-(Tentner, 2010). The particle bed height is one of the key quantitative parameters to clarify the debris bed coolability (Dinh, 2008, Park, 2013, Yakush, 2009, Yakush, 2009). Keeping this in mind, the present experimental data would be useful on developing an empirical correlation for the reasonable estimation of particle bed characteristics, particularly bed height during the process of particle sedimentation. Furthermore, validation and verification of numerical models and simulation codes require fundamental experimental data. In this perspective the present experimental results of the particle sedimentation behaviour have a good application scope. We believe that due to high cost and prolonged duration of the experimental process our validated computer code can be useful as an effective numerical tool to clarify the debris bed formation mechanism better with reasonable extrapolation to reactor conditions.

In the present study, particle bed formation characteristic was studied to shed light onto the debris sedimentation process in terms of some crucial factors: nozzle diameter, particle density, particle diameter and nozzle height. The main objective of the present study is to investigate the particle bed characteristics under different particle sedimentation behaviour. The particle bed characteristics essentially configure the particle bed shape. This particle bed shape can rationally be projected on the basis of some quantitative characteristics of the bed as expressed by four key quantitative parameters: mound height, mound dimple area, dimple volume and repose angle of the mound. The general purpose of the present experimental study is to understand the basic behaviour of particle sedimentation on bed formation mechanism as a separate effect. The main aim of the present study is to investigate

the particle bed characteristics for the diversity of particle sedimentation behavior under different particle falling conditions. In connection to evaluate the particle bed characteristic, a dimensionless empirical correlation was developed with a view to estimate the particle bed height based on the data obtained in the experimental observations. Dimensional analysis technique was applied to develop this empirical correlation as a function of various properties of solid particles used as stimulant debris, interacting fluid used as coolant as well as funnel's nozzle. The proposed correlation, after further improvement, can be incorporated into advanced fast reactor safety analysis codes and is expected to promote future simulation of debris sedimentation in CDAs of SFRs. In addition, mechanistic simulation of an accident sequence in a CDA is requisite to realistically estimate the energetic potential during PAMR phase. This can only be achieved by using a comprehensive computational tool that systematically models multi-phase thermohydraulic phenomena (Morita, 1994). From this view point our developed computer code has an application scope in clarifying the debris bed formation mechanism with reasonable extrapolation to reactor conditions.

1.6 Scope and outline of the study

To investigate the particle sedimentation behaviour on bed formation characteristics, a series of experiments was performed by gravity driven discharge of solid particles from a view point of safety investigation of the SFRs. Particle bed characteristics in terms of mound height, mound dimple area, dimple volume, and mound repose angle were investigated. In this study, both spherical and non-spherical particles were used in the sedimentation experiments. The consideration of non-spherical particle effectively clarified the role of particle shape on changing the

mound shape. The present sedimentation experiments enabled us to identify the fundamental physical characteristics of the bed shape under a simplified experimental condition. Particle sedimentation was conducted by discharging solid particles from nozzles of different diameters. We considered three nozzle positions during particle sedimentation to investigate the effect of particle fall height on forming the particle bed shape. An empirical correlation has been development based on the present experimental database by applying dimensional analysis technique. Finally, we performed numerical simulations using DEM to model the sedimentation behaviour of the solid particles to reproduce the experimental results reasonably.

The whole thesis is assembled into five chapters. The first chapter introduces the background and the objective of the present study. Chapter 2 describes the particle sedimentation experiments by gravity driven discharge. In Chapter 3, the development of empirical correlation is presented. Chapter 4 describes the numerical simulations of particle sedimentation by DEM based model. Chapter 5 draws conclusions of the thesis and briefly discusses future work.

Chapter 2

PARTICLE SEDIMENTATION EXPERIMENTS BY GRAVITY DRIVEN DISCHARGE

To investigate the effect of particle sedimentation behavior on developing the variable characteristic of bed shape, a series of basic experiments was performed from the view point of SFR safety analysis. In the present experiments, both the spherical and non-spherical particles were taken. We used four crucial factors: nozzle diameter d_n , particle density ρ_p , particle diameter d_p , and nozzle height H_n to evaluate their effect on the particle sedimentation behavior. In the course of particle sedimentation, particle mass flux in the particle jet corresponding to the particle density and nozzle diameter exhibit a crucial role on forming the mound shape, particularly the height of the particle bed. We observed that during gravity driven discharge, a substantial proportion of the released particle constitutes the core part of the particle jet; intensely fall down on the particle collector plate forming either a convex or concave type particle bed depending on the effect of the crucial factors. Only a tiny proportion of the released particle is dispersed laterally as a result of fluid resistance during particle-fluid interactions while falling through the water column.

2.1 Experiments

2.1.1 Experimental apparatus

The diagram of the experimental apparatus used in the particle sedimentation experiment is shown in **Fig. 2-1**. In the experiments, solid particles and water simulate the fuel debris and coolant, respectively. The main components of the

apparatus are the vessel and the particle injection funnel. The vessel is a cylinder, 375 mm in diameter and 1020 mm in height, made of transparent acrylic. The vessel was filled with water up to a height of 825 mm by pouring water from the top site of the vessel. At the top of the vessel, a particle injection funnel is placed on a separate structural base at 1217 mm height. The diameter of the funnel is 350 mm at the upper end (i.e., wide part) and 53.5 mm at the lower end (i.e., narrow part). The height of the funnel is 405 mm along its axial direction. A 92 mm long nozzle is attached at the lower part of the funnel with keeping its lower end at 720 mm height from the particle collector tray. The tray has an area of 1104 cm² and is located at the bottom of the vessel. The lower end of the nozzle was immersed in the water column of the vessel by maintaining water levels 105 mm above the release point of the nozzle. In the experimental runs, a stopper rod with a conical end was inserted into the funnel to plug the release hole, which prevented the solid particles flowing out during filling. The cylindrical vessel was placed inside an outer rectangular pool of transparent acrylic and the gap between the cylindrical vessel and rectangular pool was filled up by water to reduce the effect of refraction while taking online video camera photography of the experiment events. A rigid structural base was provided at the bottom of the vessel to take care of the “particle tray” and to bear the load of the water column. The entire set-up was supported by a fixed stand to minimize the effect of the mechanical vibration. A front-lighting system was equipped at a suitable vertical height to ensure the image contrast with high quality. To record the whole experimental process of particle sedimentation a digital video camera was employed, which can record tens of frames per second.

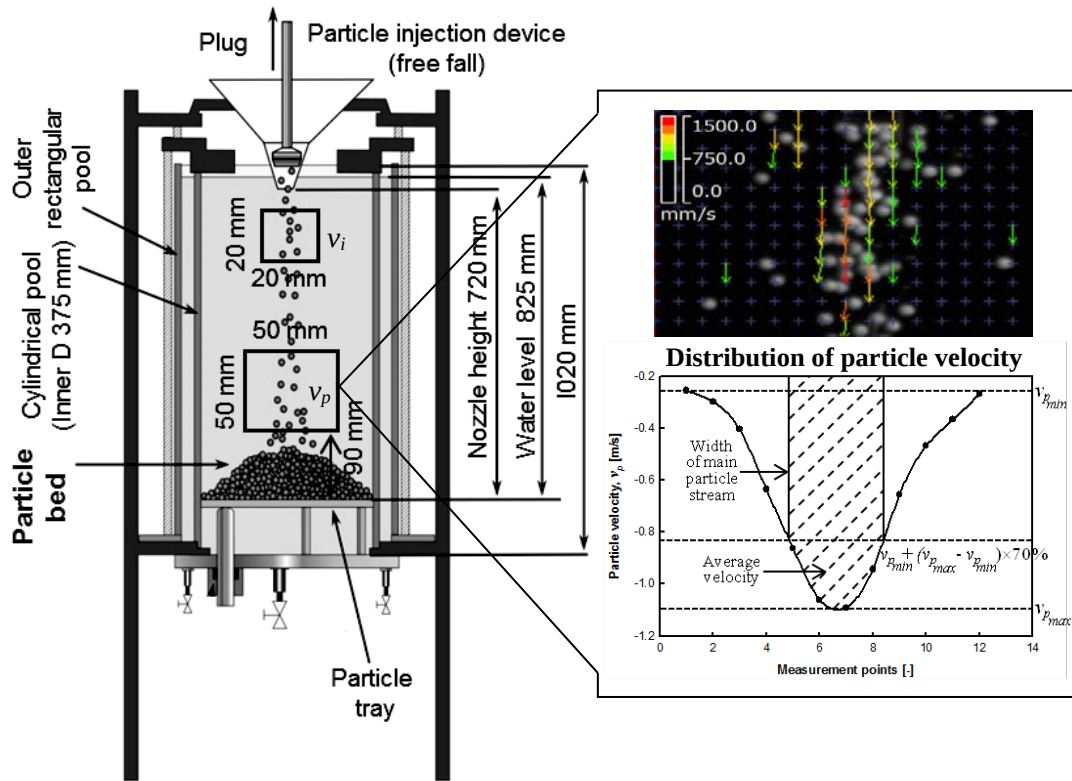


Fig. 2-1 Diagram of experimental setup.

2.1.2 Experimental procedure and conditions

A series of particle sedimentation experiments was performed by using solid particles as simulant debris focusing on the bed formation behavior owing to its significance on the coolability aspects of the debris bed. Currently, both spherical and non-spherical particles were used in the sedimentation experiments. Fig. 2-2 shows a photograph of the stimulant particles.

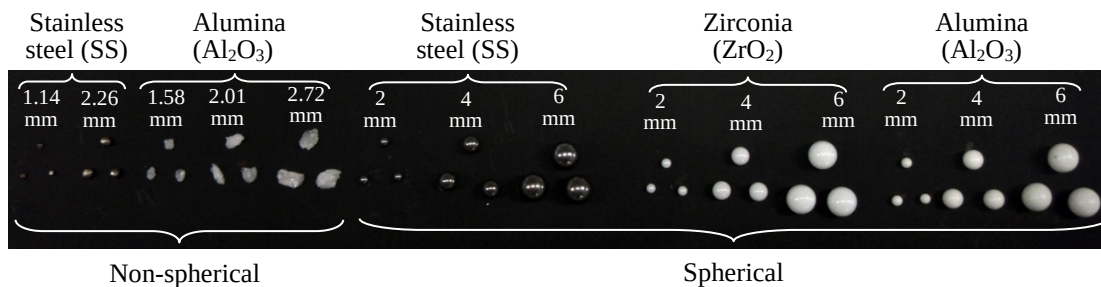


Fig. 2-2 Range of stimulant particles used in the experiments.

The present experiments were carried out to study the particle bed characteristics during particle sedimentation with an intention to evaluate the effects of four crucial factors: d_n , ρ_p , d_p and H_n on the bed shape. The experiments were performed by gravity driven discharge of solid particles into the quiescent water pool of the cylindrical vessel under isothermal conditions at a room temperature of 25°C. The immersion of the nozzle head into the water was ensured to reduce air bubble generation during particle settling process in all the experiments. In the experimental runs, solid particles with bulk volume of 5 L were released from the nozzles of different diameters ranging from 20 to 40 mm with an intention to simulate the debris bed formation scenario. The funnel (i.e. particle injection device) was filled with solid particles after plugging the release hole with a stopper rod as a pre-process of commencing the particle sedimentation. In the present experiments, we used the spherical particles with 2, 4, and 6 mm in diameter and the non-spherical particles with 1.14, 158, 2.01 and 2.72 mm in volume equivalent diameter (Fan, 1998). The nozzle outlet was located at the level of 473, 630 and 720 mm from the bottom of the pool. The solid particles with a gross volume of 5 L were then released by lifting the stopper rod from a nozzle. The discharged particles from each nozzle height finally accumulate on the particle tray, forming a particle bed with a convex or concave mound. The experimental conditions are summarized in **Table 2-1**.

Table 2-1 Experimental conditions

Particle diameter [mm]	Gross particle volume [L]	Nozzle diameter [mm]	Nozzle height [mm]	Water column height [mm]
1.14 - 6	5	20 - 40	473 - 720	825

A chump of the discharged solid particle is consisted either of spherical or non-spherical particles respective to individual experiment, and its measured

porosity in the funnel ranging from 32% to 41% for spherical particle and from 39 % to 57% for non-spherical ones. Currently, three types of solid particles of Alumina (Al_2O_3), Zirconia (ZrO_2) and stainless steel (SS) were employed to study the particle sedimentation behaviour in the case of spherical particles. For the non-spherical particles only Al_2O_3 and SS materials were taken into the experiments. In the present study, we observed an effective influence of the particle sphericity on the particle sedimentation behavior. The sphericity ϕ of non-spherical particle was determined by Ergun's equation (Wen, 1966). The physical properties of the solid particles are shown in **Table 2-2**.

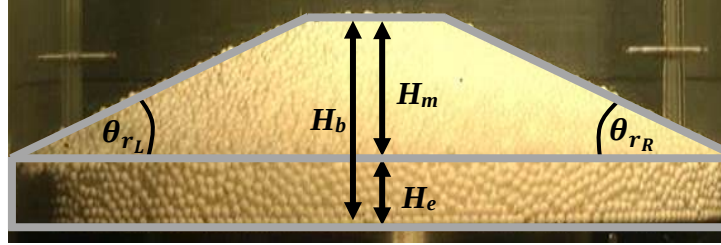
Table 2-2 Physical properties of solid particle

Materials	Shape	Sphericity [-]	Diameter [mm]	Density [kg/m ³]	Porosity [%]
Al_2O_3	Spherical	1	2	3,600	39
	Spherical	1	4	3,600	39.5
	Spherical	1	6	3,600	40
	Non-spherical	0.43	1.58	3,600	52
	Non-spherical	0.44	2.01	3,600	56
	Non-spherical	0.40	2.72	3,600	57
ZrO_2	Spherical	1	2	6,000	32
	Spherical	1	4	6,000	36.5
	Spherical	1	6	6,000	39
SS	Spherical	1	2	7,800	34
	Spherical	1	4	7,800	38.5
	Spherical	1	6	7,800	40.5
	Non-spherical	0.82	1.14	7,800	42
	Non-spherical	0.74	2.26	7,800	39

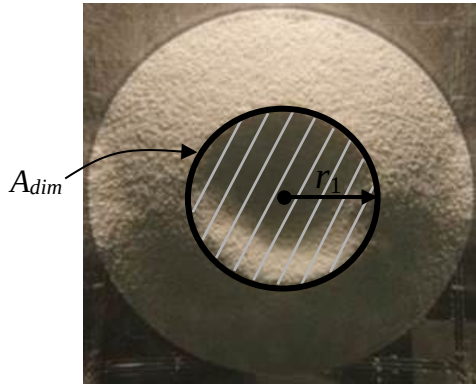
In the experiments, we focus our attention to evaluate the effects of the aforesaid four crucial factors on the bed shape and found that the particle

sedimentation characteristic can change based on the effects of these factors. Based on the understanding of the current experimental observations, it is believed that the appearance of the bed shape can be in different fashion based on the degree of impact of different crucial factors. Consequently, for quantitative evaluation, bed shape was expressed in terms of four key quantitative parameters: mound height H_m , mound dimple area A_{dim} , mound dimple volume V_{dim} as well as mound repose angle θ . **Fig. 2-3** shows the illustration of measured parameters, which present the characteristics of particle bed shape. The H_m is defined as the height of the particle bed's heap at the axis of symmetry (i.e. middle point of the particle collector plate's breadth), which is quantified by subtracting the bed edge height H_e from the particle bed height H_b measured along the axis of symmetry, as shown in Fig. 2-3 (a). The H_m of different particle bed was compared to estimate the relative variation in the mound elevation for comparative analysis. The elevation of H_m depends on the elevation of H_b . The circular cavity created on the mound of particle bed during particle falling process is defined as a dimple. The area A_{dim} of the dimple was measured by approximating its circumference as a circle and hence $A_{dim} = \pi r_1^2$, where r_1 was measured from the top view of the photographic image, as shown in Fig. 2-3 (b). The dimple volume V_{dim} was estimated by subtracting the bulk particle volume from the measured apparent bed volume. The bulk particle volume, which is the gross one including void, is 5 L in the present experiments, while the apparent bed volume is the side-viewed superficial one including the dimple volume. The definition of the apparent bed volume and the relevant variables are schematically presented in Fig. 2-3 (c). The apparent bed volume is equal to $(V_A + V_B)$, where $V_A = \frac{1}{3}\pi(r_1^2 + r_1 \cdot r_2 + r_2^2)H_m$ and $V_B = \pi r_3^2 H_e$. It is well understood that A_{dim} and V_{dim} can be the useful indicator for the analysis of the convexness or concaveness of the

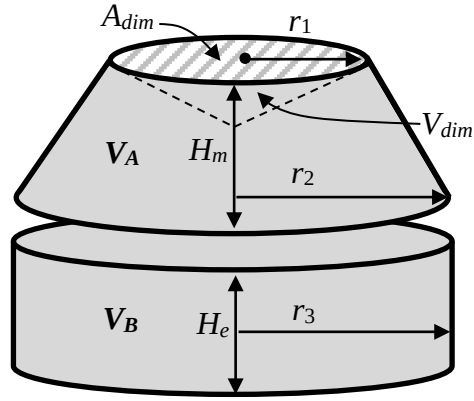
mound. The repose angle is estimated as $\theta_r = \frac{(\theta_{r_L} + \theta_{r_R})}{2}$, where θ_{r_L} and θ_{r_R} are the repose angles observed on the left and right side of the debris bed, respectively.



(a) Mound height H_m



(b) Dimple area A_{dim}



(c) Dimple volume V_{dim}

Fig. 2-3 Illustration of measured parameters to present the characteristics of particle bed shape.

In the present study, the particle velocity v_p (i.e., velocity of the falling particle) was measured around the mound top of the particle bed, as shown in Fig. 2-1. The physical meaning of this velocity points out the impact velocity of those particles which reside along the main stream of axial particle flux during its fall down.-This particle velocity is measured by the method of particle image velocimetry (PIV) using image analysis tool. In the quantitative analysis of velocity, a test section of $50 \times 50 \text{ mm}^2$ area was selected at 90 mm above the particle tray focusing the track of main stream particle flow to generate the velocity data by capturing the image of those particles which are passing through the selected area of

the test section. The width of the main stream particle flow was measured corresponding to $v_{p_{min}} + (v_{p_{max}} - v_{p_{min}}) \times 70\%$ of velocity distribution and its average velocity was defined as the particle velocity (Fig. 2-1). In addition, with an intention to generalise the present experimental conditions in terms of the particle exit velocity, we measured the initial particle velocity v_i at the nozzle outlet by using the same technique as v_p , (Fig. 2-1). To measure v_i with the PIV method, a test section of $20 \times 20 \text{ mm}^2$ area was selected at 20 mm bellow the nozzle outlet in order to capture the image of the main stream particles which are passing through this area.

Throughout the current experiments, we confined our attention solely on studying the influence of controllable crucial factors in forming particle bed shape with a view to categorize their effect on particle sedimentation. One of the prime objectives of the present study is to identify the key quantitative parameters for the purpose to comprehend their effects on altering mound shape of the particle bed.

2.2 Analysis of experimental results and discussion

2.2.1 General behavior of bed shape for spherical particles

In the present experiments, formation of Gaussian-type convex and ring-type concave bed shape was noticeably observed during particle sedimentation process under different experimental conditions. The concave shaped bed is defined as one with a dimple formed on the mound top, whereas the bed without dimple formation is called the convex type. The diversity of bed shape mainly depends on several physical parameters, such as, nozzle diameter, particle density, particle diameter, and nozzle height, which are considered as the governing crucial factors. Consequently, bed shape transformation phenomena from convex to concave is appeared based on the effect of these crucial factors together with particle velocity and particle mass

flux. The convex shaped bed is apparently prone to be formed during particle sedimentation with small size nozzle, and eventually transformed into the concave one with increasing nozzle size. This phenomenon of forming convex bed is also observed when particle sedimentation commenced with low density particles, and turns into the concave one with increasing particle density. The particle diameter is found to be another crucial factor, which exhibits a remarkable role in forming convex shaped bed with relatively larger size particles. This convex shaped bed transforms into the concave one when particle size is decreased. The similar trend of forming convex shaped bed was seen when particle falling nozzle height is reduced, and then transforms into the concave shape during particle falling with elevated nozzle height. The particle velocity and mass flux was identifies as another two factors which essentially transform the bed shape. In this case, the convex shaped bed transforms into the concave type when either the particle velocity or the mass flux is larger than a certain value. In transforming the bed shape, nozzle diameter pronounced relatively larger effect in comparison of the other factors which plays key role in changing the bed shape. In all the cases of bed shape transformation, H_m was observed in decreasing fashion with subsequent decrement of θ_r , when convex shaped bed turns into concave one in terms of the increased nozzle diameter and particle density as well as particle diameter and nozzle height.

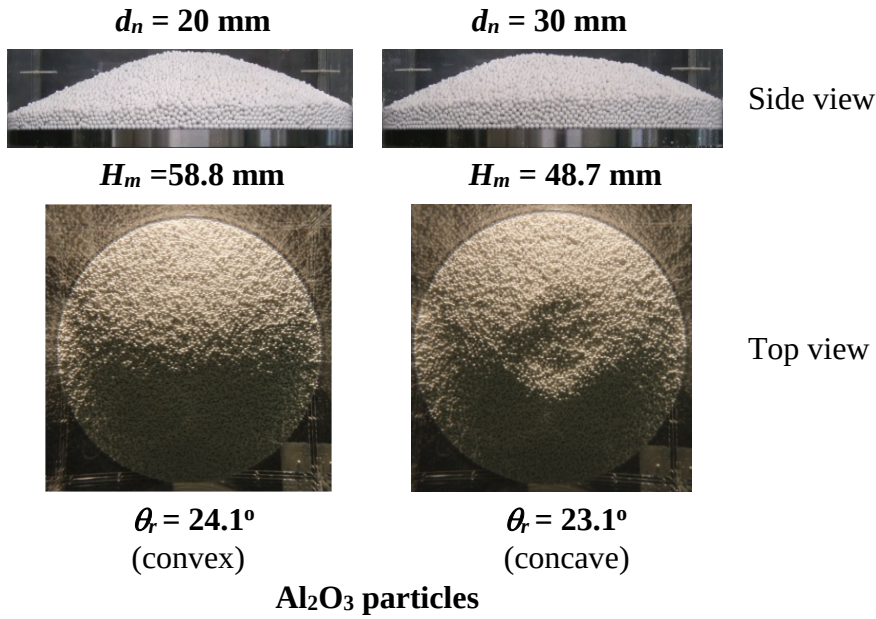
2.2.2 Criterion of bed shape transformation for spherical particles

The criterion of bed shape transformation is evaluated in terms of the main crucial factors together with particle velocity and mass flux, which act as driving factors on transforming the bed shape. The evaluated general behavior of bed shape transformation reveals a distinct role of these factors on changing the bed shape in

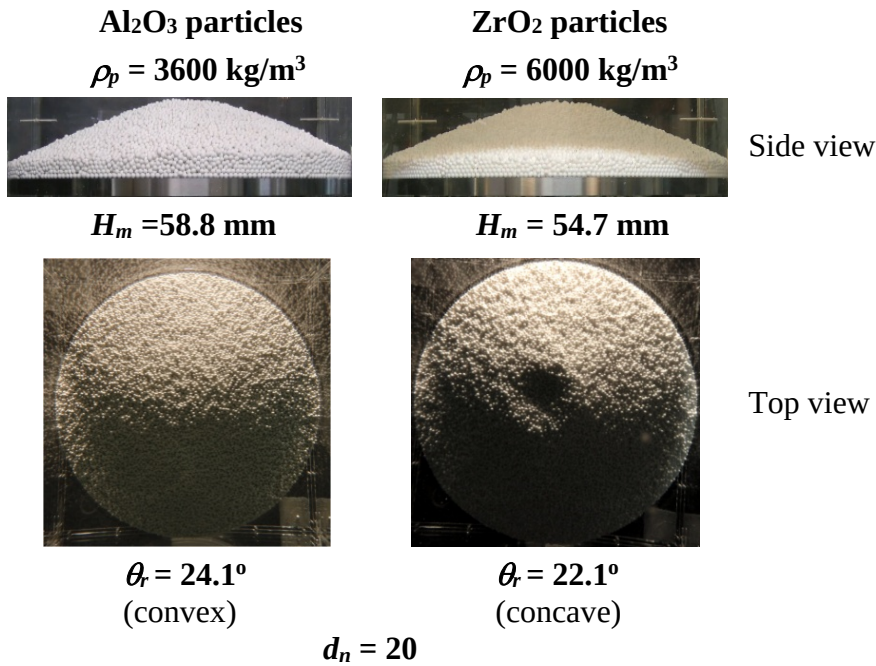
the present experiments as generally discussed in the Section 2.2.1. The qualitative discussion on the criteria of the bed shape transformation is presented in the following section based on the effect of these crucial factors.

Fig. 2-4 (a) and (b) show the typical photographs of the bed shape transformation from convex to concave with increased nozzle diameter and density, respectively. In Fig. 2-4 (a) a convex shaped bed appears with $d_n = 20$ mm, which then turns into the concave one when nozzle diameter was increased to 30 mm for the spherical particles of Al_2O_3 with $d_p = 4$ mm, $H_n = 720$ mm. Similarly, a convex shaped bed transformed into the concave one when particle density 3600 was increased to 6000 kg/m^3 with $d_n = 20$ mm for the same d_p and H_n as mentioned above (Fig. 2-4 (b)). These photographs point out that the bed shape can noticeably be transformed based on the individual role of the nozzle diameter and particle density. Based on this understanding the qualitative analysis of the bed shape transformation is schematically presented in **Fig. 2-5**. From this figure it is seen that bed shape would essentially be convex when the nozzle size and the particle density is smaller than a certain value. This convex shaped bed will eventually transform into the concave one if either the nozzle size or the particle density is increased above a certain value under the present experimental conditions. Consequently, the role of this increased nozzle size and particle density is recognized as one of the criteria for transforming the bed from convex to concave shape. In the course of bed shape transformation, the concavity was observed in increasing fashion with increased nozzle diameter. This is mainly due to the reason of increased effect of the impact force of particle jet acting per unit area of the mound top causing strong jet-mound interactions, which then push out the settling particles radially depending on the nozzle size. The impact force can be defined as the collisional force with which the

settling particles strike the sediment particles by transferring the momentum during collision. When bed shape transforms from convex to concave under present experimental condition, θ_r was observed in decreasing fashion due to the decrement of the mound height as well as the subsequent increment of the dimple size.



(a) Bed shape transformation with nozzle size.



(b) Bed shape transformation with particle density.

Fig. 2-4 Typical profile of bed shape transformation ($d_p = 4 \text{ mm}$; $H_n = 720 \text{ mm}$).

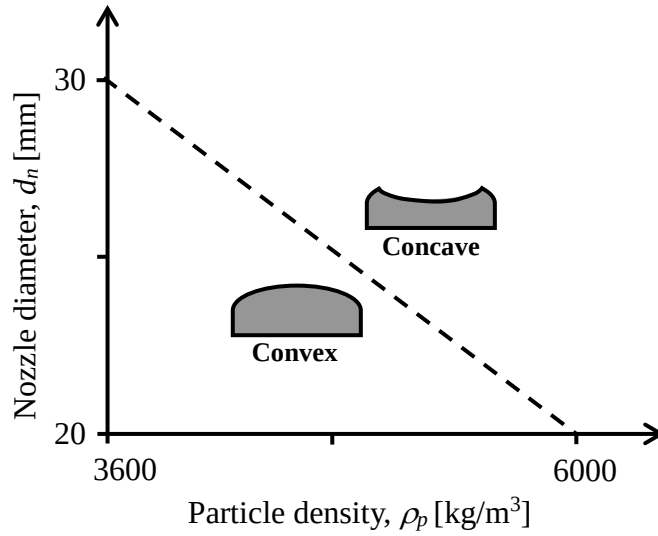
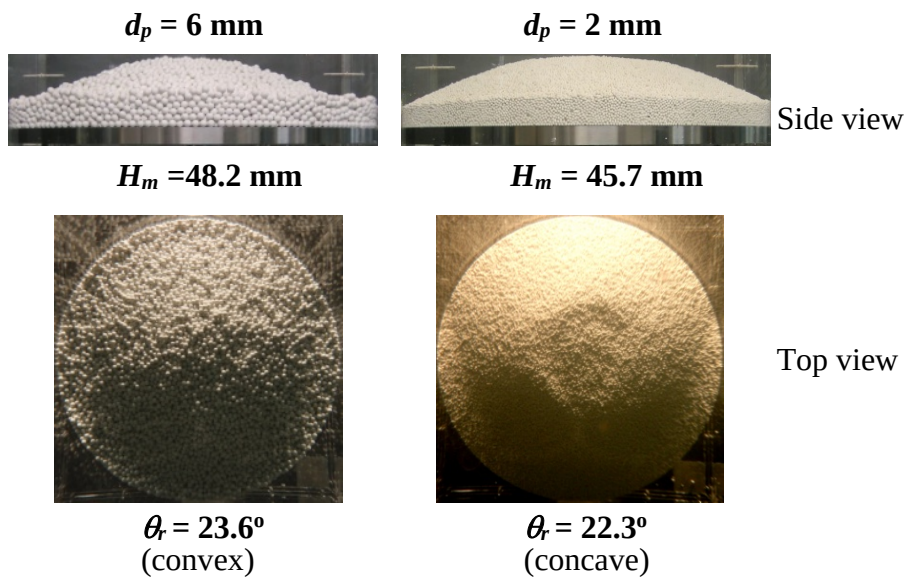


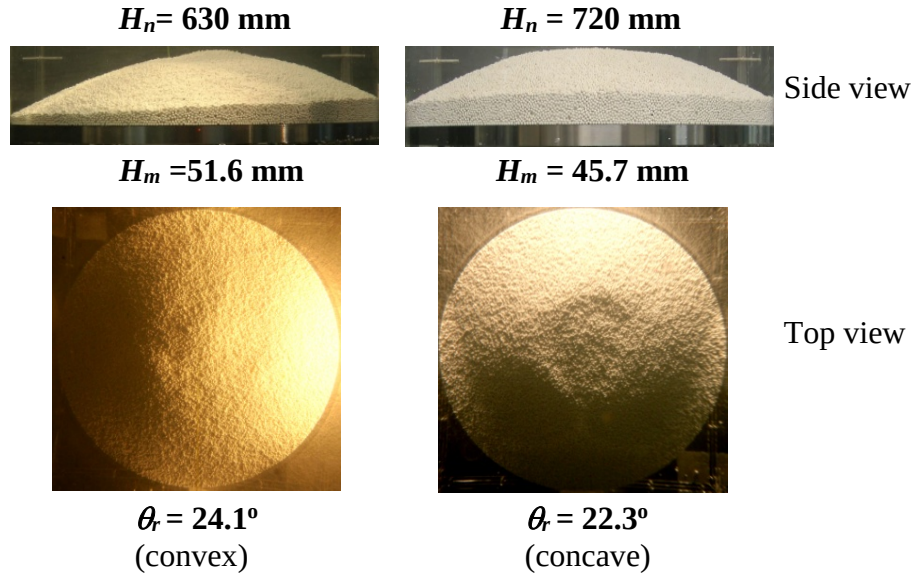
Fig. 2-5 Criterion of bed shape transformation in terms of nozzle diameter and particle density ($d_p = 4$ mm; $H_n = 720$ mm).

In the course of bed shape transformation, particle size and the nozzle height were identified as other two factors, which pronounced remarkable role in this process. **Fig. 2-6** (a) and (b) present the typical photographs of the bed shape transformation in terms of particle size and nozzle height, respectively. From Fig. 2-6 (a) we observed the formation of a convex shaped bed with $d_p = 6$ mm, this bed shape then turns into the concave one when the particle diameter was decreased to 2 mm for the spherical particles of Al_2O_3 with $d_n = 30$ mm. This observation signifies that smaller particles are prone to form a concave shaped bed. In a similar fashion, the convex bed was formed with particle sedimentation from the nozzle height 630 mm and then a subsequent transformation of the bed shape into the concave one was appeared when the nozzle height was increased to 720 mm in the case of Al_2O_3 particles with $d_p = 2$ mm, as shown in Fig. 2-6 (b). This observation signifies the tendency of forming a concave shaped bed with particle sedimentation from relatively a large nozzle height. Based on the above observations, the conversion process of the convex shaped bed into the concave one is schematically

demonstrated in **Fig. 2-7**. This figure indicates that if the particle size is larger than a certain value, bed shape will essentially be convex type. Subsequently, if the particle size is decreased below a certain value, bed shape will transform into the concave one under the present experimental conditions (Al_2O_3 particles; $d_n = 30$ mm; $H_n = 720$ mm). On the other hand, bed shape will rationally be convex type if the nozzle height becomes smaller than a certain value. However, when the nozzle height is increased beyond a certain value bed shape will turn into the concave one under same experimental conditions. Therefore, based on the present observation the effect of the particle size and nozzle height is acknowledged as the additional criterions of bed shape transformation. When bed shape transforms from convex to concave under the effect of the particle size or nozzle height, mound height was observed in decreasing fashion indicating a decreasing trend in θ_r . It is noted that the effect of particle size and nozzle height is relatively small than the other two factors on forming the concave shaped bed.



(a) Bed shape transformation with particle size ($H_n = 720$ mm).



(b) Bed shape transformation with nozzle height ($d_p = 2 \text{ mm}$).

Fig. 2-6 Typical profile of bed shape transformation (Al_2O_3 particles; $d_n = 30 \text{ mm}$).

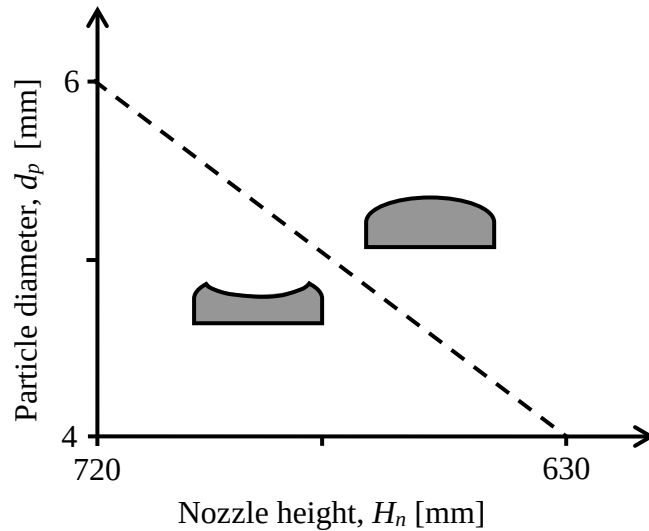


Fig. 2-7 Criterion of bed shape transformation in terms of particle diameter and nozzle height (Al_2O_3 particles; $d_n = 30 \text{ mm}$).

The similar transformation of bed shape from convex to concave was also observed based on the role of the particle velocity v_p and particle mass flux j_m variation. The schematic description of the bed shape transformation in terms of v_p and j_m is presented in **Fig. 2-8**. From this figure it is seen that bed shape would

basically be convex if either the particle velocity or the mass flux is smaller than a certain value in the case of Al_2O_3 particles. This convex shaped bed will ultimately be transformed into the concave one when either the particle velocity or the particle mass flux goes beyond a certain value under the present experimental conditions ($d_p = 4 \text{ mm}$ and $H_n = 720 \text{ mm}$). The mass flux is defined as the rate of mass flow per unit area per unit time at the nozzle outlet and was calculated by using a formula, presented by

$$j_m = \frac{V_p \rho_p (1-\varepsilon)}{(A \cdot t)} \quad (2-1)$$

where, V_p is the bulk particle volume, ρ_p is the particle density, ε is the porosity, A is the cross-sectional area of the nozzle and t is the particle falling time.

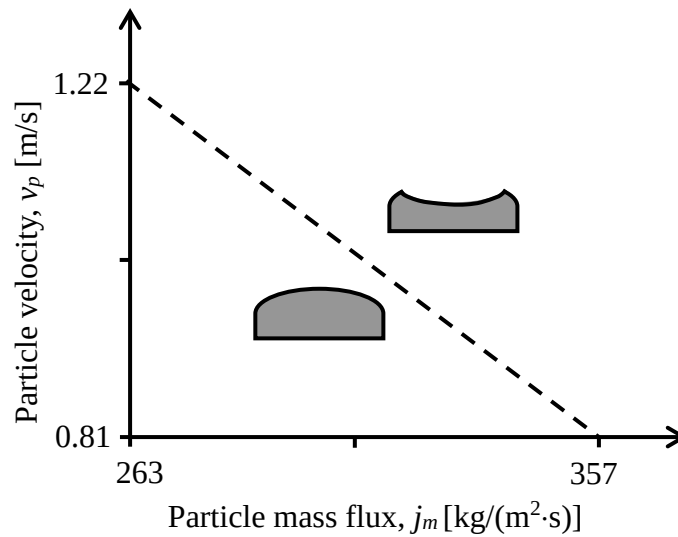


Fig. 2-8 Criterion of bed shape transformation in terms of particle velocity and mass flux of Al_2O_3 particles ($d_p = 4 \text{ mm}$; $H_n = 720 \text{ mm}$).

Throughout the process of bed shape transformation it is well understood that the effect of the nozzle diameter, particle density, particle diameter as well as nozzle height together with the particle velocity, and the particle mass flux play a crucial role in developing the concave shaped bed. In this context, the role of three parameters: particle velocity, particle density and the particle mass flux among the

aforesaid six parameters can essentially be useful to express the particle jet property. Consequently, to evaluate the transformation of bed shape in terms of the combined effect of the particle velocity, density and the mass flux, we formulate a dimensionless jet factor J_f to express the effect of the particle jet on the bed shape transformation. This factor is simply defined as the ratio of a term, consists of particle density multiplied by particle velocity, to the particle mass flux. The physical meaning of jet factor signifies the ratio between the particle inertia force at the nozzle outlet to the particle impact force on the mound top. Based on the role of this jet factor the transformation of bed shape from convex to concave was observed in terms of forming the mound dimple area. Accordingly, an effective role of the jet factor on the variation of the dimple area is recognized in the course of forming a concave shaped bed, as shown in **Fig. 2-9**. From this figure it can be seen that the formation of the dimple area was not observed at smaller than a certain value of the jet factor in the case of the 4 mm particles of Al_2O_3 and SS, whereas the jet factor at which no dimple appears in the case of 4 mm particle of ZrO_2 is estimated from the linear regression equation, $J_f = -0.028 \times A_{dim} + 11.827$.

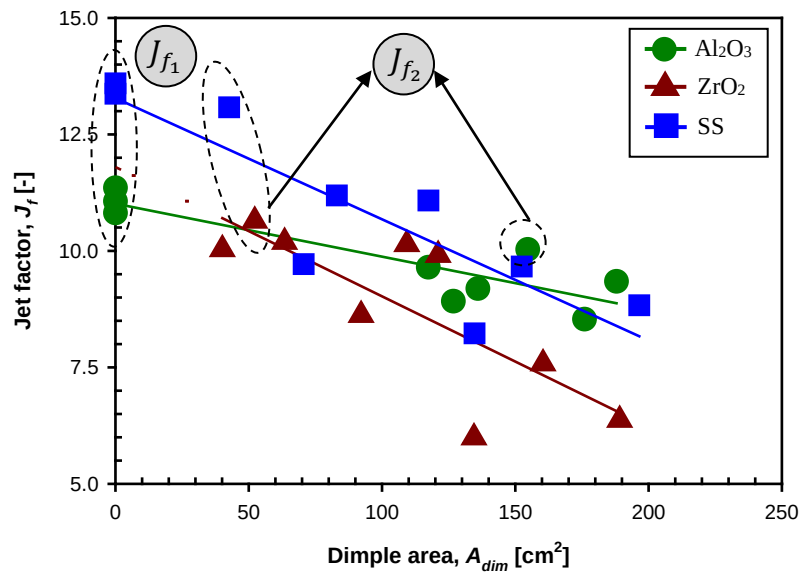


Fig. 2-9 Variation of dimple area with jet factor ($d_p = 4$ mm).

Based on this observation it can be summarized that at larger than a certain value of the jet factor i.e., at J_{f_1} the dimple area does not appear, which reasonably indicates the formation of convex shaped bed in the case of above mentioned three particles. Therefore, the quantitative conditions of forming convex bed are $J_{f_1} \geq 11.0$, $J_{f_1} \geq 11.8$ and $J_{f_1} \geq 13.3$ for Al_2O_3 , ZrO_2 and SS particles, respectively. On the other hand, development of the dimple area appears at a certain value of the jet factor J_{f_2} which is smaller than J_{f_1} and indicates a remarkable formation of concave shaped bed in the cases of these particles. Therefore, the quantitative conditions of forming concave bed are $J_{f_2} \leq 10.0$, $J_{f_2} \leq 10.6$ and $J_{f_2} \leq 13.1$ for Al_2O_3 , ZrO_2 and SS particles, respectively. Thus, in between of these jet factor values in forming convex and concave bed, there should be a critical jet factor J_{f_c} , below which bed shape will essentially be concave. Therefore, the general condition of transforming bed shape from convex to concave can be written as $J_{f_1} \geq J_{f_c} \geq J_{f_2}$. The schematic description of the bed shape transformation based on the jet factor condition is depicted in **Fig. 2-10**. In this figure the shaded zone lying in between of J_{f_1} and J_{f_2} indicates the potential values of the critical jet factor J_{f_c} . Based on this illustration, it can be summarized that bed shape will essentially be convex type when the jet factor becomes larger than a certain critical value. Eventually, bed shape will transform into the concave one when the jet factor becomes smaller than a certain critical value. It is also noticed in Fig. 2-10 that both J_{f_1} and J_{f_2} indicates an increasing tendency when the particle density is increased. In addition, the shaded zone is observed gradually narrowing with an indication of small difference between J_{f_1} and J_{f_2} in the case of denser particles. This observations point out the necessity of

larger value of the critical jet factor for the convex to concave bed shape transformation in the case of relatively dense particles.

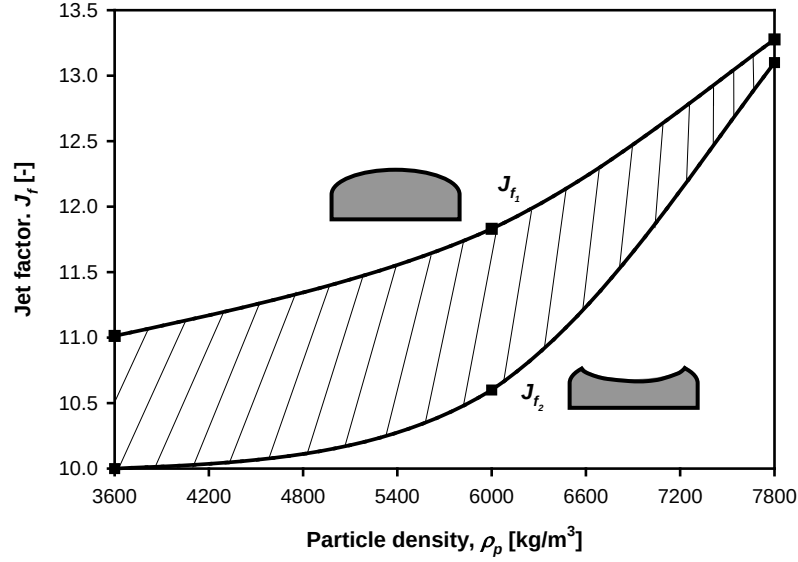


Fig. 2-10 Bed shape transformation based on jet factor ($d_p = 4$ mm).

2.2.3 Quantitative characteristics of concave shaped bed for spherical particles

The quantitative characteristics of the bed shape have been discussed based on the role of the crucial factors in forming the concave shaped bed. To investigate the quantitative characteristics of the bed shape we select four key quantitative parameters: H_m , A_{dim} , V_{dim} and θ . The evaluation of the bed shape in terms of the aforesaid key quantitative parameters has been performed based on the effect of the four crucial factors: d_n , ρ_p , d_p and H_n . In the course of the particle sedimentation process, this four crucial factors greatly influence the impact of the particle jet on developing the concave shaped particle bed, as discussed in the following sections.

Fig. 2-11 shows the typical bed shapes corresponding to the nozzle size and density effect in the case of Al_2O_3 , ZrO_2 and SS particles with $d_p = 4$ mm. This

figure distinctly implies larger effects of nozzle size than the density effect on the variation of the particle bed profile in terms of dimple area and volume.

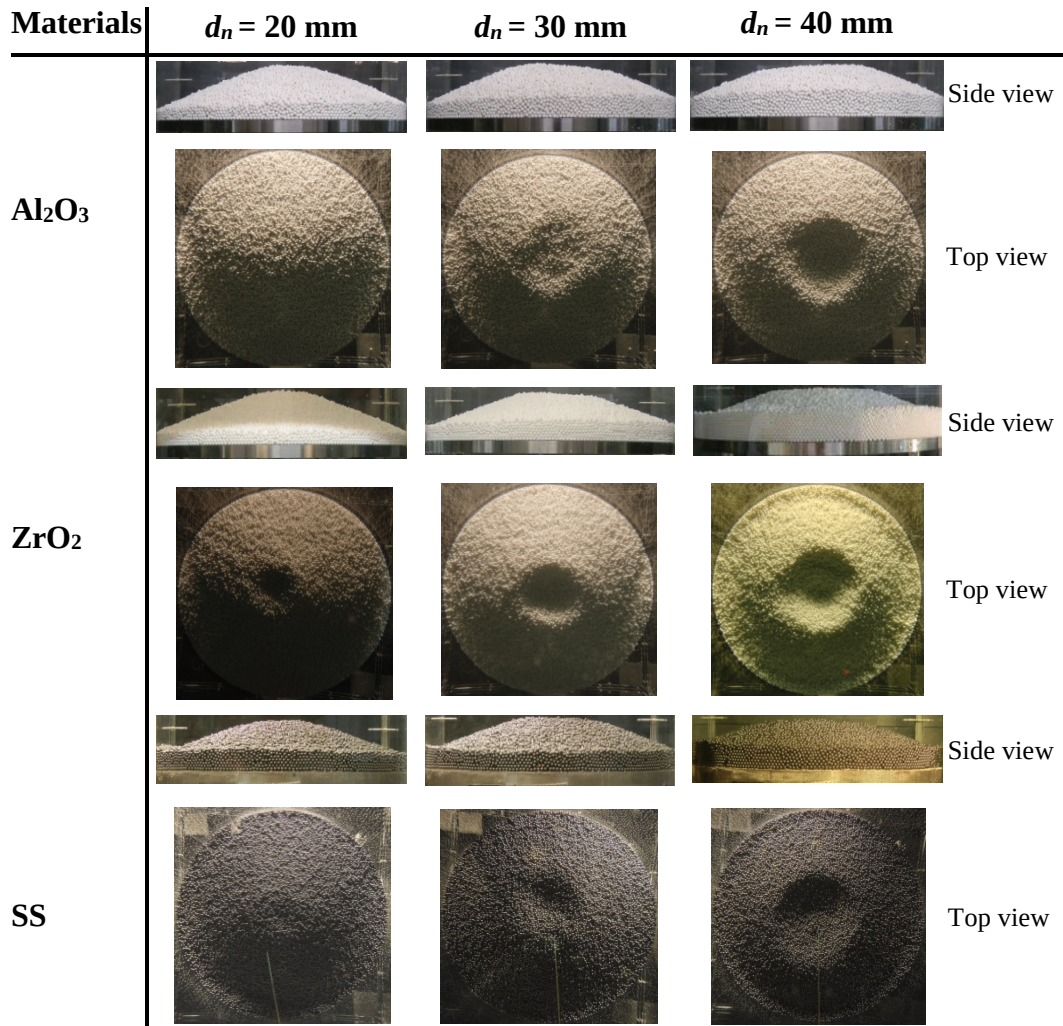


Fig. 2-11 Photographs of particle bed shapes under different conditions of nozzle size and particle density ($d_p = 4 \text{ mm}$; $H_n = 720 \text{ mm}$).

Fig. 2-12 shows the quantitative effect of the nozzle diameter and the particle density on the bed shape in the case of $H_n = 720 \text{ mm}$ and $d_p = 4 \text{ mm}$. We expressed the bed shape in terms of four subsequent key quantitative parameters. Fig. 2-12 (a) exhibits a descending trend of H_m variation with nozzle diameter in the case of $d_p = 4 \text{ mm}$ for Al_2O_3 , ZrO_2 and SS particles with density of 3600 , 6000 and 7800 kg/m^3 , respectively. From this trend of H_m variation it can be summarized that mound

contour will possibly transform into a flatten shape when sediment particles discharge through a wider relocation path. This is mainly due to the reason of larger gravity impact in the case of intense fall pattern of the wider particle jet. The dimple area is found in an increasing trend with the nozzle diameter, as shown in Fig. 2-12 (b), indicating the formation of the concave shaped bed with $A_{dim} > 0$. The reason of increasing A_{dim} with the nozzle diameter is mainly due to the increment of the jet diameter causing a subsequent increment of the interaction area on the top of the bed while interacting with sediment particles. The gradual increment and eventual formation of larger A_{dim} with $d_n = 40$ mm signifies the formation of a flatten mound as H_m was observed decreasing with the increment of A_{dim} in the experiments (Fig. 2-15 (a), which will be discussed later). In connection to express the bed shape in terms of dimple volume V_{dim} , the variation of V_{dim} on the mound of the particle bed was investigated. We found V_{dim} in an increasing manner with increased nozzle diameter, as shown in Fig. 2-12 (c), where $V_{dim} > 0$ means that the mound of particle bed is formed into a concave shape. The reason of increasing V_{dim} with the nozzle diameter is mainly increment of the particle mass flux in the core part of the jet, which consequently causes larger gravity impact of the particle jet on the top of the bed during particle jet–mound interactions. The formation of larger V_{dim} with increasing nozzle diameter indicates the decrement of H_m which causes an eventual level off of the mound (Fig. 2-15 (b)). Fig. 2-12 (d) depicts the variation of θ_r of the particle bed indicating a decreasing fashion with increasing nozzle diameter. The reason of decreasing θ_r with nozzle diameter is mainly due to the increment of lateral particle sedimentation resulting an eventual decrement of H_m .

In the case of particle density effect, larger elevation in H_m was found in the case of light particles than the case of heavy ones, as shown in Fig. 2-12 (a). This

figure also indicates that the difference in H_m became smaller when particle density gradually increased to a larger value for all the nozzle cases. This general trend indicates a possibility of forming an elevated mound in the case of low density particles deposition. The variation of A_{dim} and V_{dim} with increasing density was not recognized in a regular fashion when particle bed was formed with $d_n = 20$ mm, as shown in Fig. 2-12 (b) and (c). A larger variation in A_{dim} and V_{dim} were observed for particles with different densities in the case of $d_n = 20$ mm with non-appearance of a dimple for Al_2O_3 particles with $\rho_p = 3600 \text{ kg/m}^3$. The reason of not forming a dimple might be the insufficient impact of the particle jet on the top of the bed in the case of relatively light particles than that of the heavier ones. Both A_{dim} and V_{dim} was found relatively larger in the case of ZrO_2 particles with density of 6000 kg/m^3 , whereas larger particle-particle frictional drag resists particles to sediment laterally with forming relatively small A_{dim} and V_{dim} in the case of SS particles with density of 7800 kg/m^3 for $d_n = 20$ mm. In the case of $d_n = 30$ mm, the variation of A_{dim} was found in decreasing fashion with increasing particle density, although this trend of variation did not exist in the case of V_{dim} variation. Consequently, a difference in dependency of A_{dim} and V_{dim} on the particle density for $d_n = 30$ mm was observed. This is because the formation larger A_{dim} , as observed in the case of Al_2O_3 particles, mainly depends on the jet diameter. On the other hand, formation of larger V_{dim} rationally depends on the jet impact force, which is reasonably larger in the case of larger density particles. Therefore, the formation of small V_{dim} in the case of light Al_2O_3 particles is rational due to small effect of the particle jet impact on the top of the bed. However, the reason of forming larger V_{dim} for ZrO_2 particles is mainly due to larger jet impact with subsequent smaller particle-particle frictional drag in comparison of the SS particles. On the other hand, relatively small quantitative difference was observed

among A_{dim} , and V_{dim} for the three particle densities in the case of $d_n = 40$ mm. This is because of comparable size of the jet width which comprises a larger particle mass flux in all the cases with $d_n = 40$ mm. This observation indicates that these three types of particles can possibly form a similar bed shape in terms of the dimple volume when the nozzle size is relatively larger. From Fig. 2-12 (d) we can see the density effect on the variation of θ_r . A general descending trend of θ_r was observed with density. This might be due to the reason of larger mound elevation of the light particles, reasonably causing larger θ_r than heavy ones. The trend of density dependency of θ_r can potentially be useful as an indicator to express the degree of levelling of dissimilar particles bed shape.

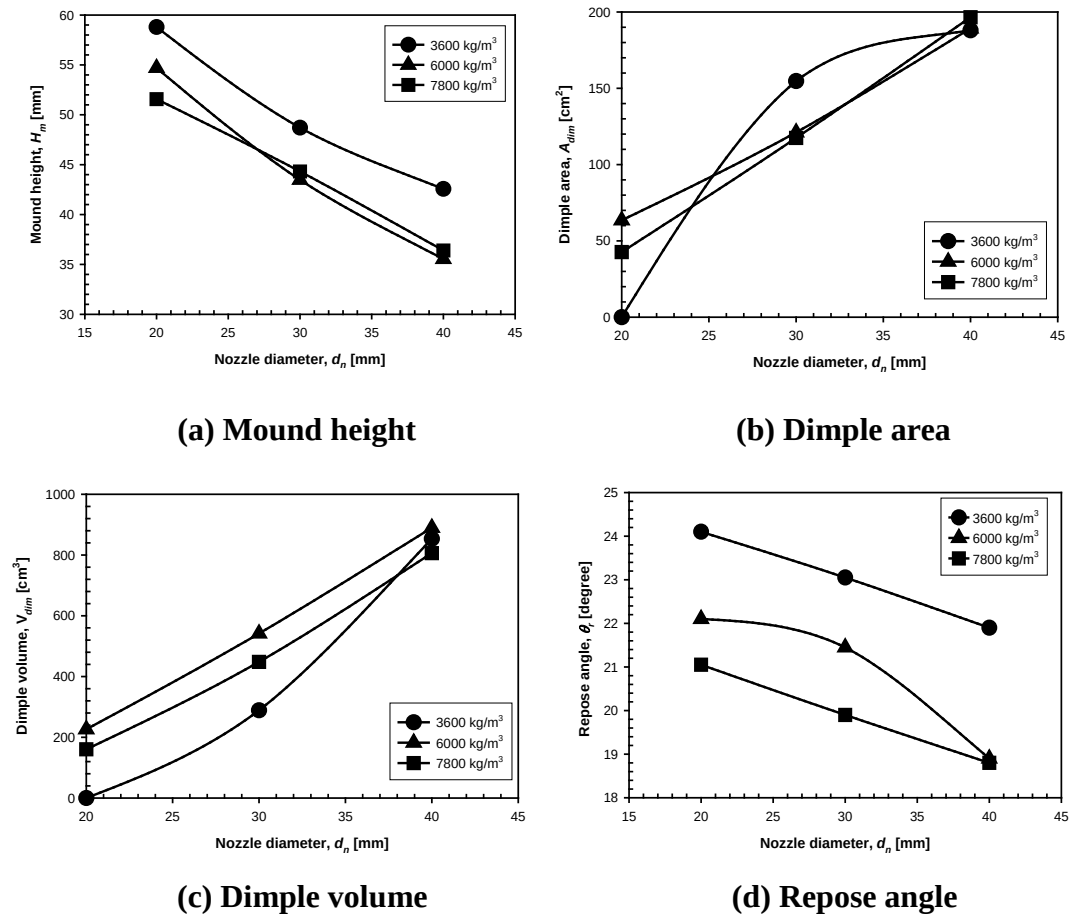


Fig. 2-12 Nozzle diameter and particle density effect on the particle bed shape ($d_p = 4$ mm; $H_n = 720$ mm).

The qualitative evaluation of the bed shape in terms of the nozzle height and particle size effect can be seen from the representative photographs of **Fig. 2-13**. From this demonstration of typical photographs we can acknowledge the potential role of the nozzle height and particle size on forming the outline of the bed shape.

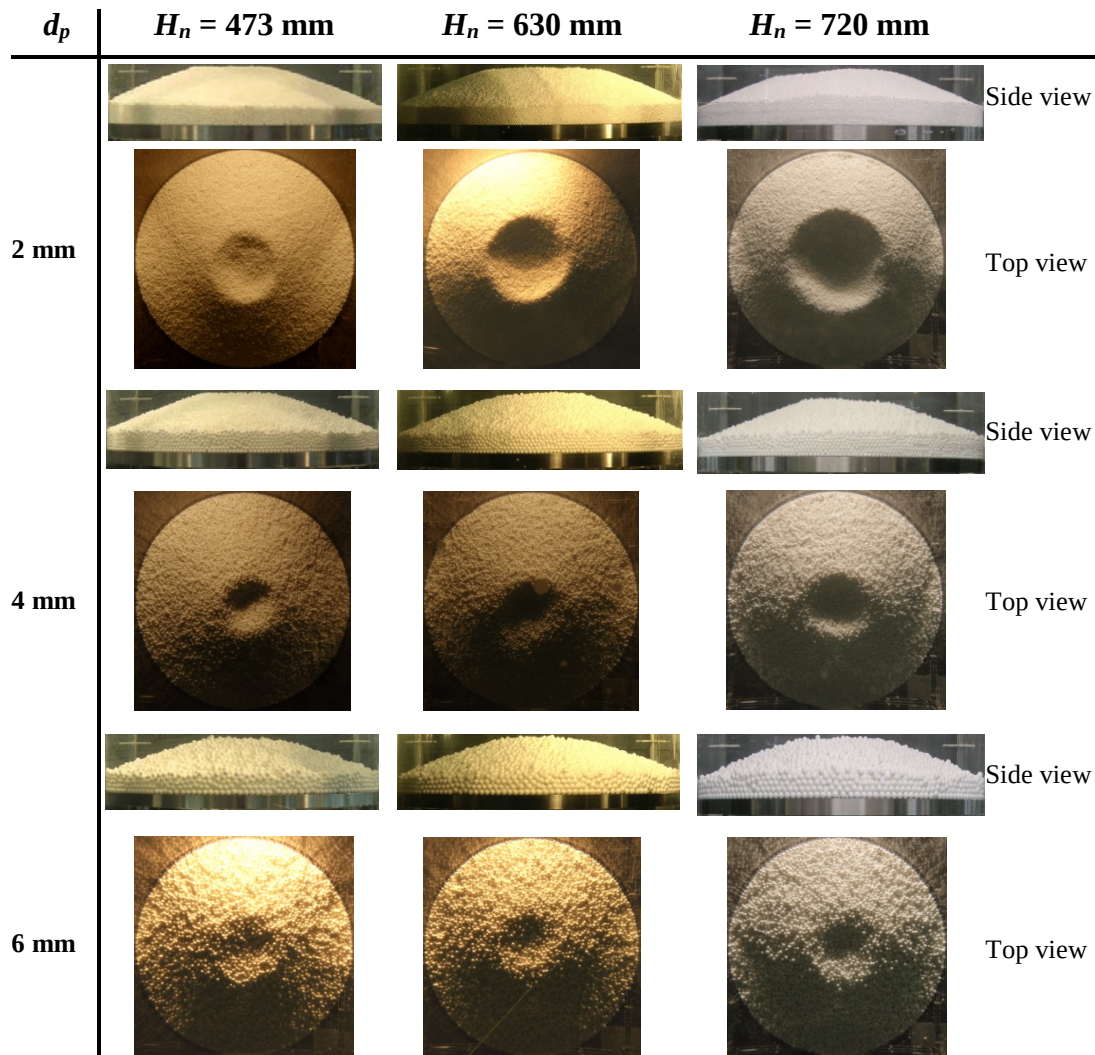


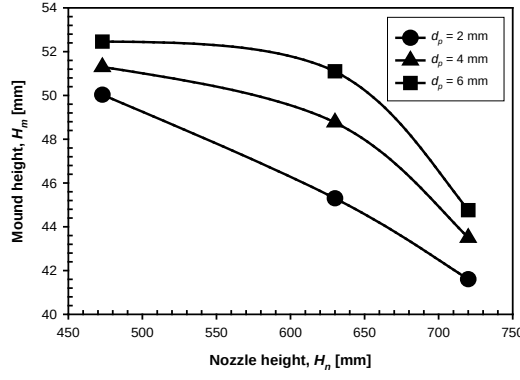
Fig. 2-13 Photographs of particle bed shape under different conditions of nozzle-height and particle diameter (ZrO_2 particles; $d_n = 30 \text{ mm}$).

Fig. 2-14 demonstrates the effect of nozzle height and the particle size on the bed shape in a quantitative manner. From this figure we can see a descending trend of H_m variation when nozzle height is increased, as shown in Fig. 2-14 (a). This tendency indicates a possibility of leveling off a mound when particles sediment

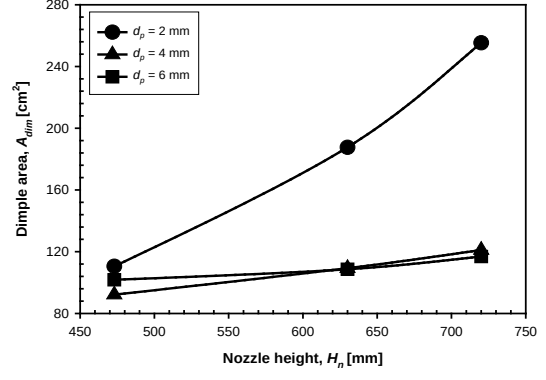
from an elevated relocation channel. This is because of larger effect of the impact force when particle jet interacts on the top of the bed. The variation of A_{dim} was found in an increasing trend with nozzle height, as shown in Fig. 2-14 (b). This is because of forming a particle jet of larger diameter with larger nozzle height which then initiates subsequent interactions with the sediment particles on the mound top covering relatively a large area. During this interaction on the top of the bed between the particle jet and the sediment particles, the impact of the particle jet of relatively large diameter initiates the lateral dissipation of particles with a subsequent formation of larger circular area of the dimple. In the present study, we recognised that the nozzle height variation also imposes an effect on varying the dimple volume, as shown in Fig. 2-14 (c). An increasing trend of V_{dim} is observed with increased nozzle height. This can be due to the reason of larger impact of interactions caused by the larger particle velocity with increasing nozzle height. This is because in our study we observed an increment of particle velocity with increasing nozzle height. Fig. 2-14 (d) demonstrates the role of the nozzle height on changing θ_r . From this figure a decreasing fashion of θ_r was observed with increasing nozzle height. This information reveal the possibility of getting a flatten shaped mound during particle fall from a larger height.

The effect of the particle size can also be seen from Fig. 2-14, where the quantitative influence of the particle diameter on the bed shape is presented. Fig. 2-14 (a) shows a relative small elevation of H_m in the case of small size particles than that of the larger ones. This observation signifies the possibility of forming a reduced mound height when molten jet would be sufficiently fragmented into small particles. From Fig. 2-14 (b) we can see the variation of A_{dim} in a decreasing trend with increased particle diameter with an exception in the case of $H_n = 473$ mm.

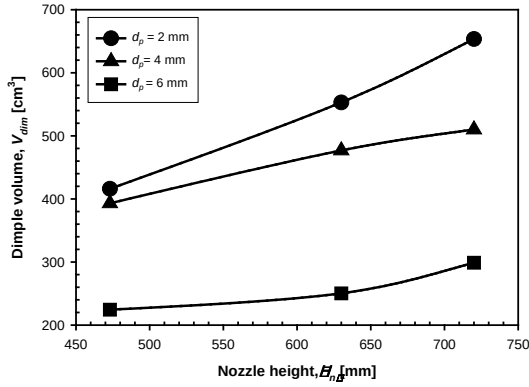
Larger A_{dim} was observed in the case of particles with $d_p = 2$ mm. This is mainly because of larger lateral sedimentation of smaller particles than that of the larger size particles caused by the interactions between the wider particle jet and sediment particles. The potential reason of forming a smaller dimple area of larger size particles can be the larger particle–particle frictions among the particles which let larger particles to be less prone to sediment laterally. Therefore, we found a noticeable variation in the dimple area in the case of particles with $d_p = 2$ mm in comparison of the larger size particles. This figure also indicates that the dependency of A_{dim} on the particle size became small as the particle size increased. Fig. 2-14 (c) depicts a decreasing trend of V_{dim} with particle size in the case of ZrO_2 particles. The reason of the decreasing tendency of V_{dim} can potentially be due to the decrement of jet impact on the top of the bed when particle size is increased. This is because in general the increment of the particle size can cause a reasonable increment of the particle–fluid interactions with a subsequent decrement of the impact force effect of the particle jet which eventually results a formation of a small dimple volume. Fig. 2-14 (d) shows the dependency of θ_r on the particle size indicating a relative small difference in the repose angles of different particle sizes because of their comparable mound heights. This figure demonstrates an increasing trend of θ_r with increased particle size for all the nozzle cases. The reason of growing θ_r with particle size mainly underlies on the formation of elevated H_m in the case of larger size particles. This gradual rising trend of θ_r signifies the potential development of a peaked mound as H_m was observed increasing with the increment of θ_r in the experiments (Fig. 2-15 (c), which will be discussed later).



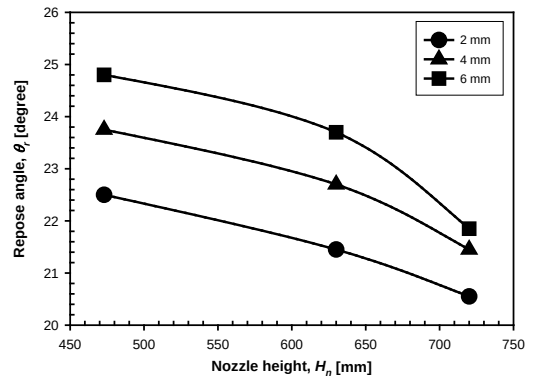
(a) Mound height



(b) Dimple area



(c) Dimple volume

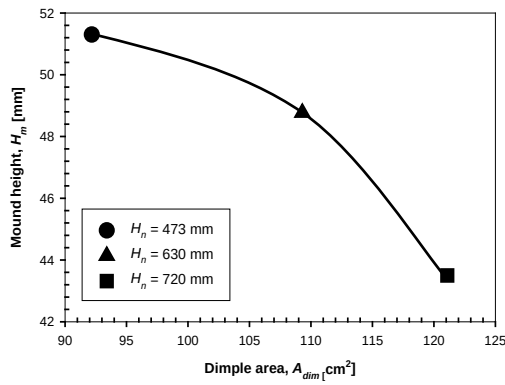


(d) Repose angle

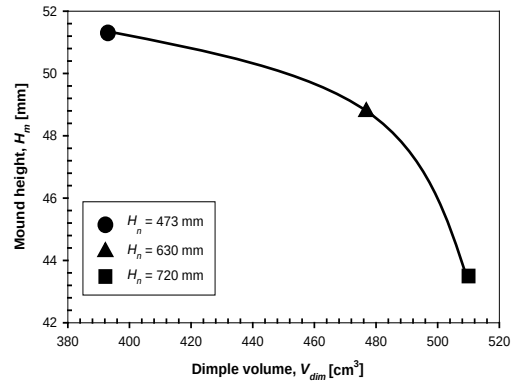
Fig. 2-14 Nozzle height and particle diameter effect on the particle bed shape (ZrO₂ particles; $d_n = 30$ mm).

In connection to clarify the debris bed coolability, H_m can essentially be a crucial factor. In this perspective, we observed the variation of H_m with respect to A_{dim} , V_{dim} and θ_r . The relationships between the A_{dim} and H_m , and between V_{dim} and H_m as well as between θ_r and H_m are analysed for the ZrO₂ particles with $d_p = 4$ mm, considering the nozzle height as the parameter in the case of $d_n = 30$ mm. This is because we did not observe remarkable dependency on particle density in a regular trend as well as the dependency of the mound height on the particle size is relatively small.

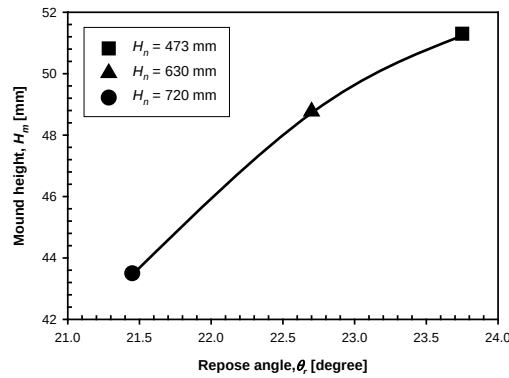
Fig. 2-15 shows the variation of H_m in terms of A_{dim} , V_{dim} and θ_r for ZrO_2 particles with $d_p = 4$ mm in the case of $d_n = 30$ mm. Fig. 2-15 (a) indicates the decrement of H_m as A_{dim} is increased. The decrement of H_m was observed in the similar fashion with V_{dim} , as shown in Fig. 2-15 (b). From this observation we recognize the significant role of A_{dim} and V_{dim} that may expedite the leveling of particle bed. Fig. 2-15 (c) presents the role of repose angle on the mound height variation. We found H_m in an increasing trend when θ_r is increased. This observation indicates a relevance of θ_r in forming the elevation of the particle bed.



(a) Effect of A_{dim}



(b) Effect of V_{dim}



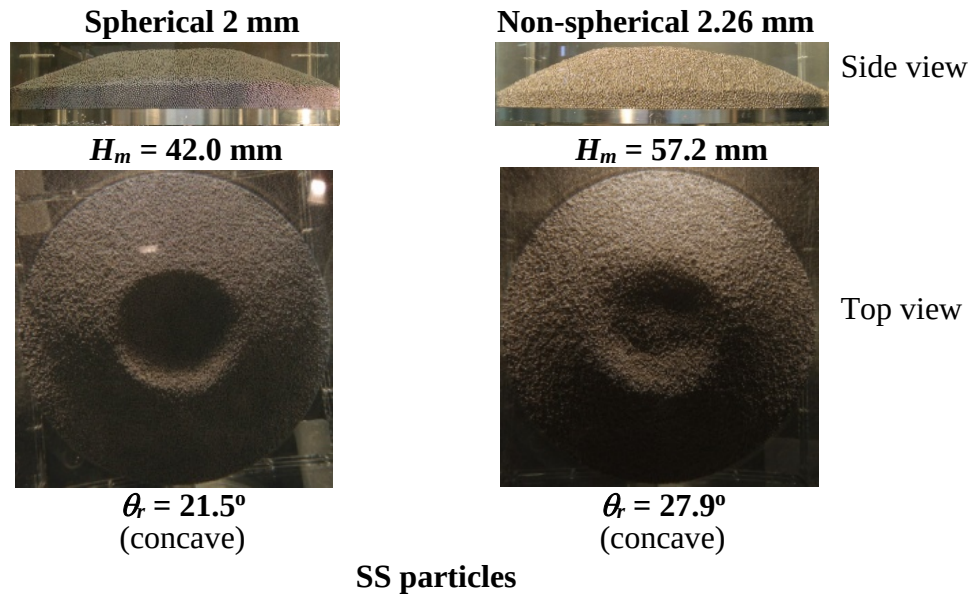
(c) Effect of θ_r

Fig. 2-15 Variation of mound height in terms of A_{dim} , V_{dim} and θ_r (ZrO_2 particles; $d_p = 4$ mm; $d_n = 30$ mm).

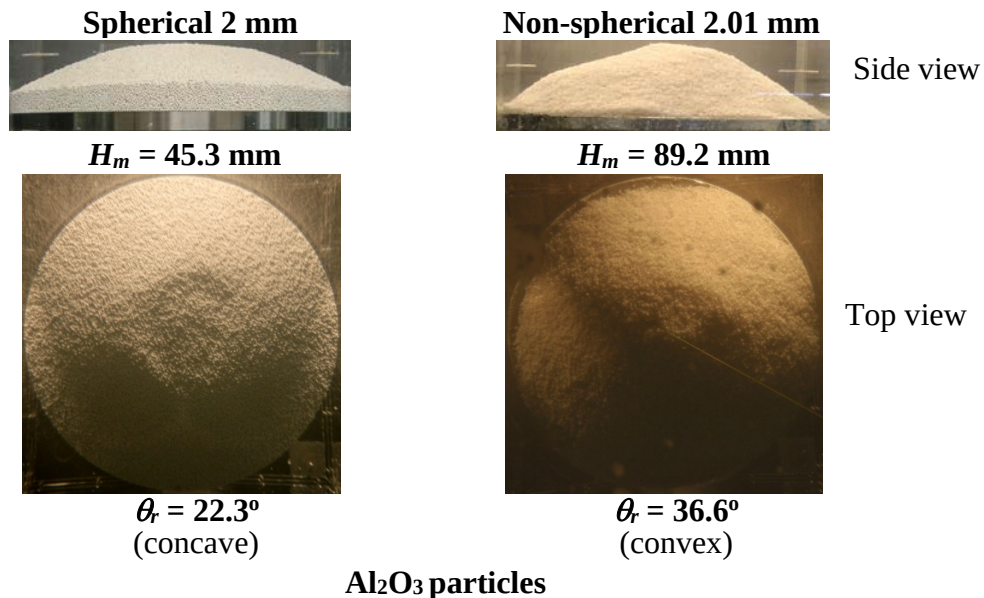
2.2.4 Representative bed characteristics for non-spherical particles

In the case of non-spherical particle sedimentation experiments, particle shape in terms of sphericity exhibits an effective role on the sedimentation pattern. The consequence of the particle shape influences the eventual formation of the mound shape of the particle bed indicating a larger mound elevation than that of the spherical particles. The mound shape refers to the variation of the mound contour in terms of the mound height across the particle collector plate. **Fig. 2-16** shows the effect of particle shape on forming the mound shape of the particle bed for non-spherical particles in comparison of the spherical ones in the case of SS and Al_2O_3 particles. From Fig. 2-16 (a) it is apparently seen that the area and depth of mound dimple appears in different forms with forming an elevated H_m based on the effect of SS particles shape. Fig. 2-16 (b) depicts the non-appearance of mound dimple with forming a relatively large mound elevation in the case of non-spherical Al_2O_3 particles. The quantitative mound shape as seen from the side in concern to the particle shape effect on changing mound height is shown in **Fig. 2-17**. This figure indicates the formation of larger elevation of the mound height in the case of the non-spherical particles than that of the spherical ones for both SS and Al_2O_3 particles, as shown in Fig. 17 (a) and (b). The potential reason of this can be slower lateral dissipation due to larger particle-particle frictional drag as well as smaller impact of the gravity force on the top of the bed. Relatively small gravity impact is possibly caused by larger particle-fluid interactions due to the effect of particle shape and surface asperity of the non-spherical particles. In the case of non-spherical particles the repose angle of the mound was observed larger than that of the spherical particles. This is mainly because of forming a larger mound height in the case of non-spherical particles, which resulted from the substantial deposition of non-spherical particles on

the top of the mound rather than sediment laterally due to larger particle-particle frictional drag. The eventual formation of a peaked mound with reduced bed edge height results a repose angle relatively larger than spherical particles. From this observation it can be summarized that in a fixed vessel diameter the mound can be formed in diverse forms based on the influence of particle shape.



(a) Typical photograph of mound shape for SS particles



(b) Typical photograph of mound shape for Al₂O₃ particles

Fig. 2-16 Effect of particle shape on the mound profile of SS and Al₂O₃ particles ($d_n = 30 \text{ mm}$; $H_n = 720 \text{ mm}$).

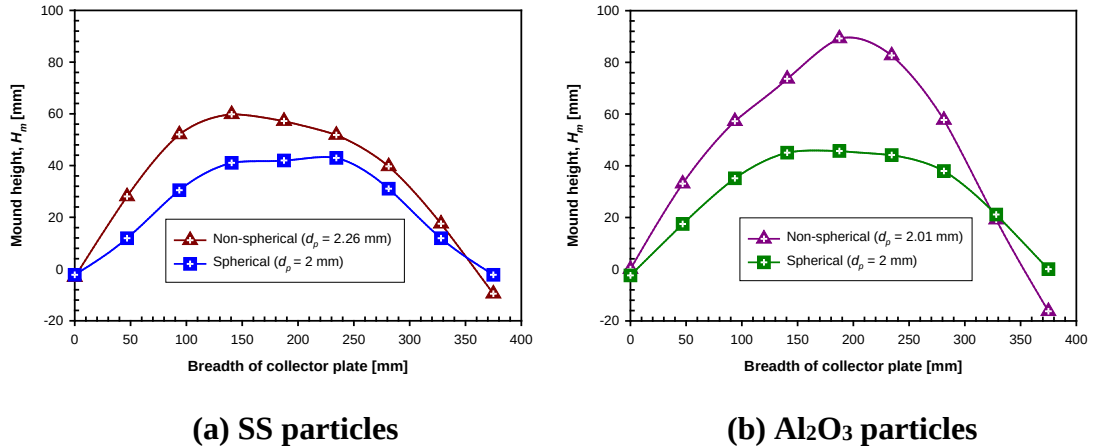


Fig. 2-17 Effect of particle shape on the quantitative mound shape ($d_n = 30$ mm; $H_n = 720$ mm).

The differences in the quantitative characteristics of the particle bed shapes for spherical and non-spherical particles are comparatively presented in **Table 2-3**.

Table 2-3 Bed characteristics of spherical and non-spherical particles of Al₂O₃ and SS ($d_n = 30$ mm; $H_n = 720$ mm).

Particle type	d_p [mm]	ϕ [-]	H_m [mm]	Mound shape	θ_r [degree]	A_{dim} [cm ²]	V_{dim} [cm ³]
Spherical	2	1	41.9	concave	21.5	178	409.8
Non-spherical	2.26	0.74	57.2	concave	27.9	183	682.2
Spherical	2	1	45.3	concave	22.3	153.6	288.1
Non-Spherical	2.01	0.44	89.2	convex	36.6	NO	NO

NO: not observed

From Table 2-3 we observed the formation of larger dimple volume in the case of non-spherical SS particles due to the impact of wider particle jet on larger mound area than that of the spherical particles with $d_n = 30$ mm. On the other hand, in the case of non-spherical Al₂O₃ particles dimple area and volume did not appear although it was observed in the case of spherical ones with the same nozzle size. This is mainly due to larger particle-particle frictional drag as well as larger effect of

particle-fluid interactions which reduced the gravity impact with subsequent decrement of the lateral sedimentation of the non-spherical Al_2O_3 particles. Eventually, a distinct difference on the bed shapes between the light non-spherical particles of Al_2O_3 and relatively heavy SS particles is appeared. The detailed quantitative characteristics of the concave shaped bed for the non-spherical particles would be evaluated under the scope of the future research work.

The variation of the mound height with repose angle in the case of non-spherical particles in comparison of the spherical ones is shown in **Fig. 2-18**. From this figure relatively larger elevation of the mound height was observed corresponding to the larger repose angles in the case of non-spherical SS particles than that of the spherical ones, as shown in Fig. 2-18 (a). A similar trend of mound height variation with repose angle can also be seen in the case of non-spherical Al_2O_3 particles in comparison of the spherical ones, as shown in Fig. 2-18 (b). It is also seen from Fig. 2-18 (a) and (b) that both the mound elevation and the corresponding repose angle were observed larger in the case of light Al_2O_3 particles than that of the heavy SS particles for both the non-spherical and spherical particles.

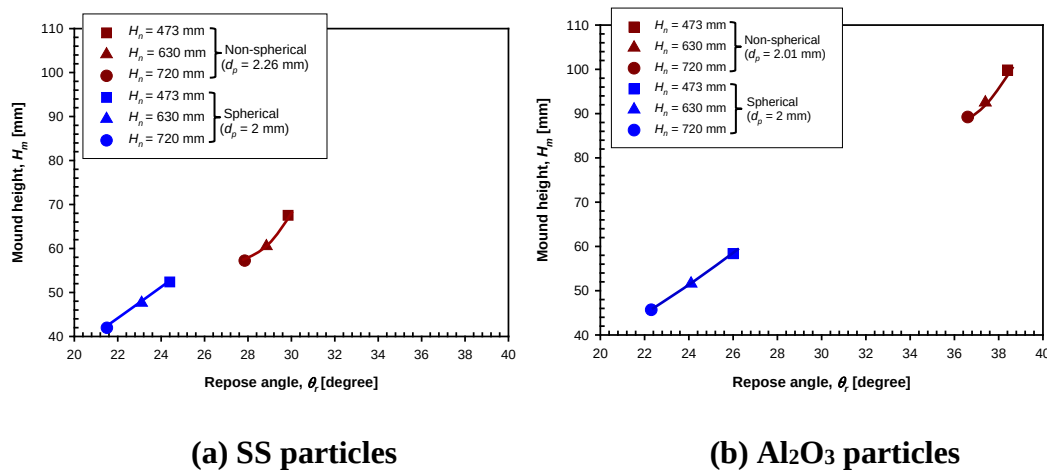


Fig. 2-18 Comparative evaluation of H_m variation with repose angle between non-spherical and spherical particles ($d_n = 30$ mm).

2.3 Summary and concluding remarks

In the present experimental study, when bed shape transforms from convex to concave we observed a variation in the concavity based on the role of the governing crucial factors. It is identified that nozzle diameter pronounced a larger influence in comparison to the role of other crucial factors during forming a concave shaped bed. The roles of the particle velocity and particle mass flux have also been identified as two additional contributing factors in transforming the bed shape. The combined effects of the particle velocity, particle density and mass flux on the bed shape transformation were expressed in terms of a dimensionless jet factor. Based on the role of this jet factor, the transformation of bed shape from convex to concave was observed in terms of forming the mound dimple area. In the quantitative assessment of the particle bed characteristics, the increasing fashion of the dimple area and volume as well as the descending trend of the mound height and repose angle implies the significant role of the crucial factors on forming the shape of the particle bed. The role of mound dimple area, dimple volume and repose angle on the variation of H_m signifies the importance of these quantitative parameters on causing a flatten mound shape. These three key quantitative parameters can possibly be recognized as the dominant factors in connection to clarify the debris bed coolability. The non-spherical particles clearly exhibit a distinct role on forming the bed shape in contrast to the spherical ones. The overall experimental results provide an indication of parameter dependency of the particle bed characteristics. Based on the current observations we can summarize that the phenomena of forming a flatten shaped bed can somehow be useful to expedite the debris bed coolability in a CDA of SFR.

Chapter 3

DEVELOPMENT OF EMPIRICAL CORRELATION BY DIMENSIONAL ANALYSIS

Dimensional analysis was performed to develop an empirical correlation in order to estimate the particle bed height H_b reasonably. In developing the empirical correlation with Buckingham's dimensional analysis technique we considered H_b instead of H_m as a dependent parameter to quantify the total bed height. The elevation of H_b in principle gives an indication of the upward development of H_m . This is because in the experimental observation we recognized the ascension of H_m in proportion to the elevation of H_b . In this study the predicted H_b was compared with the experimental results corresponding to the effect of the four crucial factors to find out their role on H_b variation. The main purpose of this study is to develop an empirical correlation so as to reproduce the experimental trend of H_b variation based on the effect of the governing crucial factors.

3.1 Dimensional analysis

The Buckingham π theorem (Buckingham, 1914) and method of indices were used for finding dimensionless groups appropriate for this problem, and a new empirical correlation was developed using multiple linear regression method. Dimensional analysis is identified as the basic key element in scaling facility used in severe accidents research program (Holowach, 2003, Zuber, 1998) and also in the design of reduced size test facilities (Kocamustafaogullari, 1983, Celso, 2004, Kayser, 1982, Wulff, 1996) for a nuclear reactor, because it facilitates scaling down a phenomenon occurring in the prototype to experimentation in the laboratory with

the option of using different working materials and fluids. Dimensional analysis consists of identifying parameters influencing any process and grouping them into a set of independent dimensionless numbers. It is a powerful tool to correlate the experimental data which are obtained by controlling the crucial factors in a systematic manner (Sudha, 2011). The power of the dimensional analysis is to reduce the number of many independent variables into small number of independent dimensionless parameters, which are completely independent of the unit system used in the measurements. In the present study dimensional analysis is carried out with an intention on deriving an appropriate set of dimensionless groups for the present system, which are subsequently correlated in a functional form. The purpose of the present dimensional analysis is to arrive at the effective dimensionless groups that can reasonably interpret the final sedimentation behavior of the solid particles, with particular emphasis on predicting H_b variation of the particle bed in a quiescent water pool.

3.1.1 Dimensional analysis for H_b of the particle bed

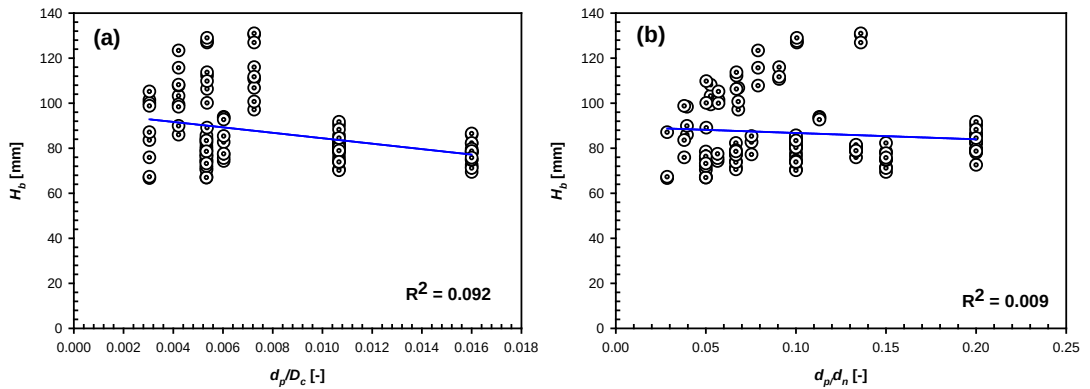
It is expected that H_b of the particle bed depends on several dimensional variables. Bearing this in mind, the variables which influencing the particle bed formation phenomenon in particle sedimentation process are listed as particle diameter d_p , particle density ρ_p , nozzle diameter d_n , nozzle height H_n , particle-fluid density difference $\Delta\rho$, net particle volume εV_p , fluid viscosity μ_f , initial particle velocity v_i , terminal velocity v_t , and cylinder diameter D_c . To introduce appropriate dimensionless products that reasonably reflect the influence of particle and fluid properties, consideration of effective parameters is emphasized in characterizing the particle sedimentation behaviour. Therefore, toward developing the empirical correlation, we considered d_p and ρ_p as the parameters to include the influence of

particle property in the sedimentation behavior. The consideration of d_n is mainly related to reflect the effect of particle relocation path. It is observed that these parameters play a significant role on the particle sedimentation behaviour during particle bed formation process. The variation of H_n can essentially impose an effective influence on varying the particle bed height and shape. This is because it affects the impact force of the particle jet during progression of the particle sedimentation and bed formation. Therefore, we believe that the consideration of H_n as a parameter can be appropriate to include the influence of the impact force on the bed top. The fifth parameter $\Delta\rho$ can reasonably express the buoyancy effect on the settling particles and is anticipated to impose an influential role during particle sedimentation process. Porosity is an important element of the particle bed, which is incorporated with the bulk particle volume to estimate the net particle volume concerning the particle packing fraction. Consequently, we included the net particle volume εV_p as a parameter to approximate the actual bed height. The inclusion of the fluid viscosity is important to interpret the particle sedimentation behaviour in fluid medium so as to reflect the fluid resistance on the settling particles. Keeping this in mind we considered μ_f as a viscosity parameter to incorporate the fluid property in the particle sedimentation process. We included v_i to generalise the experimental conditions in terms of the initial particle fall condition. It is noticed that when a particle is in a force balance state, particles of medium have reached terminal velocity v_t . Therefore, consideration of v_t can appositely be applicable in characterizing the particle sedimentation behaviour. Based on the experimental observations, the role of the cylinder size is assumed to be significant to interpret the particle sedimentation process because of cylinder interference on the settling particles due to wall effect. Hence, we consider D_c as a parameter of the present

correlation to include the role of cylinder wall effect under present experimental conditions. Then, the functional form of these variables is presented by the following equation.

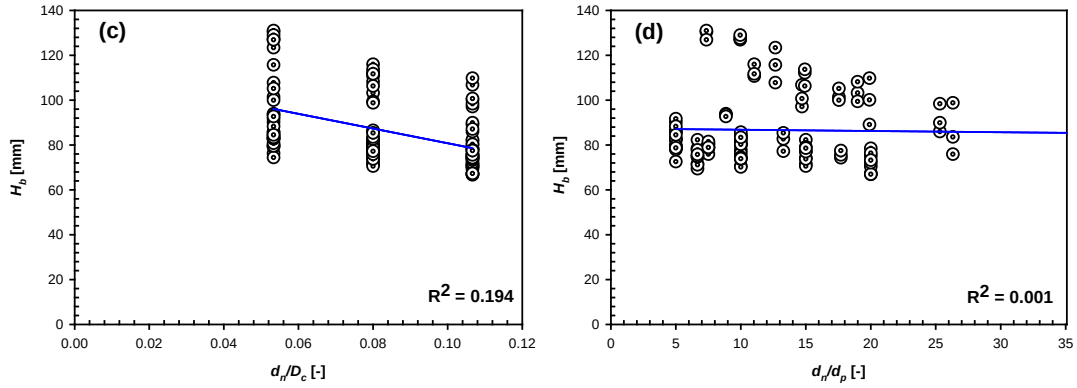
$$H_b = f(d_p, d_n, H_n, \rho_p, \Delta\rho, \varepsilon V_p, \mu_f, v_i, v_t, D_c) \quad (3-1)$$

This equation consists of 11 dimensional variables with three basic dimensions. The dimensions of all these quantities are expressed in MLT system. By using step-by-step approach, the eight prime variables are selected and another three repeated variables are found in the dimensional analysis. Hence according to Buckingham π theorem, eight dimensionless parameters would be emerged from dimensional analysis as presented in Eq. (3-2). These eight dimensionless groups were selected among several numbers of groups from different sets of dimensional analysis after identifying their role on changing H_b based on the graphical comparative evaluation, as shown in **Fig. 3-1**. It can be seen from Fig. 3-1 (a) and (b), where R^2 stands for coefficient of determination, that the trend of H_b variation in terms of d_p/D_c is relatively remarkable than that of d_p/d_n . Based on this observation we selected d_p/D_c as one of the dimensionless groups toward developing the empirical correlation.

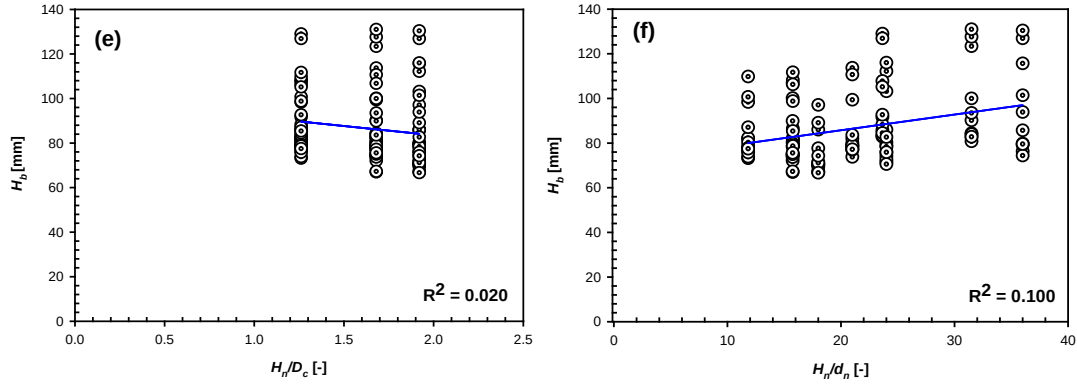


Selection of d_p/D_c in comparison of d_p/d_n

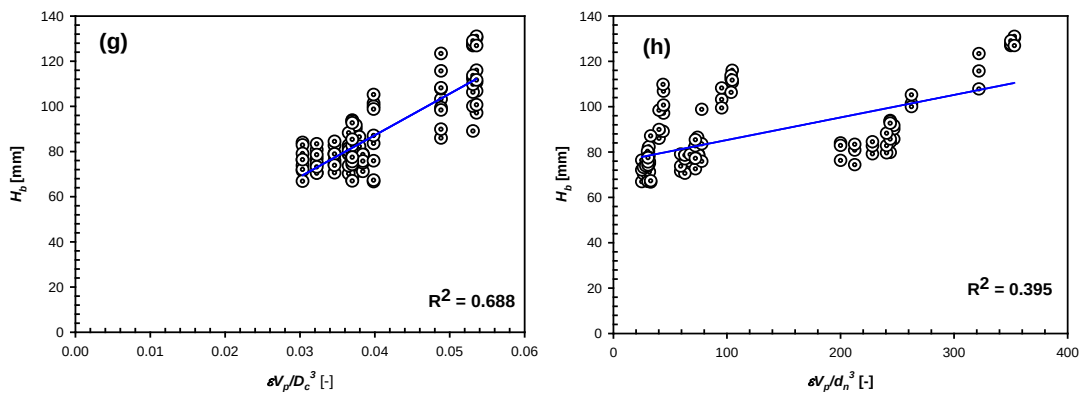
In the selection process of the remaining dimensional groups we applied the same method of graphical comparison as presented in Figs. 3-1 (c) to (j).



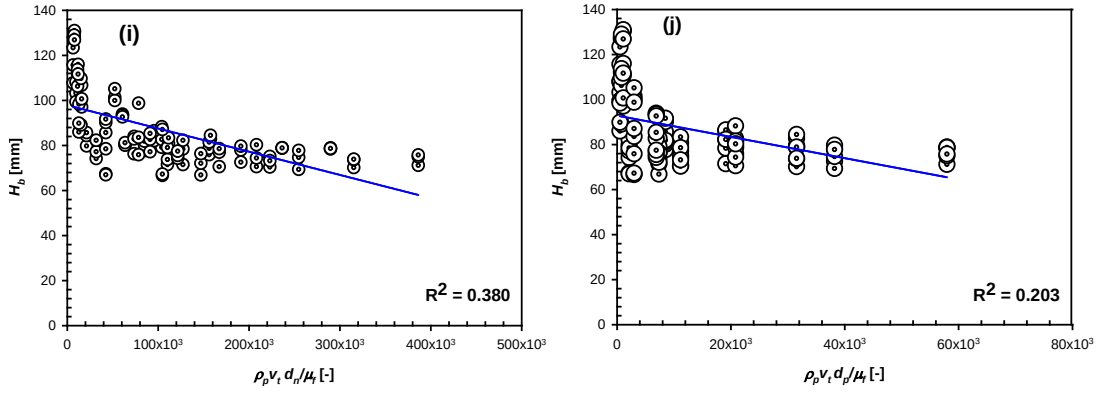
Selection of d_n/D_c in comparison of d_n/d_p



Selection of H_n/D_c in comparison of H_n/d_n

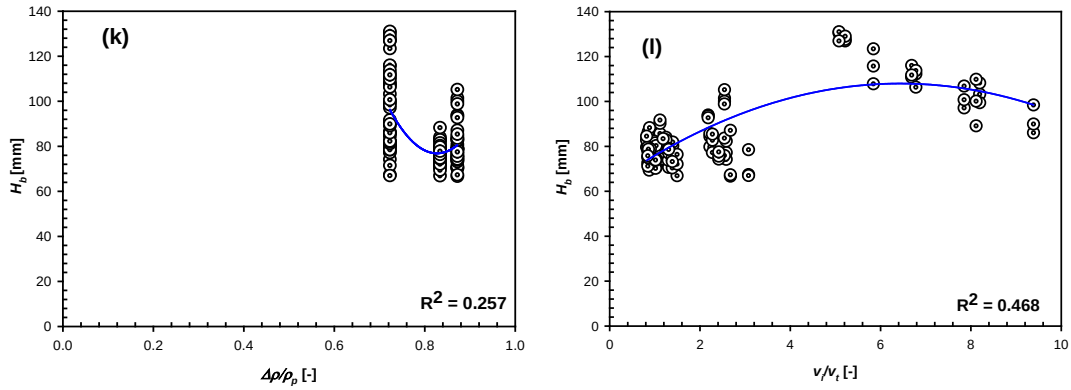


Selection of $\epsilon V_p/D_c^3$ in comparison of $\epsilon V_p/d_n^3$



Selection of $\rho_p v_t d_n / \mu_f$ in comparison of $\rho_p v_t d_p / \mu_f$

The dimensional groups presented in Figs. 3-1 (k) and (l) are considered mainly to include the buoyancy effect and initial particle fall conditions, and they were selected mainly based on their individual role on changing H_b .



Selection of $\Delta\rho/\rho_p$ and v_i/v_t based on their effect on H_b

Fig. 3-1 Selection process of the dimensionless groups based on their role on changing H_b .

In order to set a model of the finally selected eight dimensionless groups in the form of an empirical equation, a series of experimental investigations with 117 cases were carried out to obtain experimental data. The experimental cases were categorized into three groups based on three particle falling nozzle heights. In each group 39 experimental runs were performed with 24 cases for spherical particles and 15 cases for non-spherical ones. The particle sedimentation of the first group was

conducted from the nozzle height of 720 mm, whereas nozzle height of 630 mm and 473 mm were used for the second and third groups, respectively. Each group contains spherical particles of Al_2O_3 , ZrO_2 and SS materials and non-spherical particles of Al_2O_3 and SS materials with diameter ranging from 1.14 ~ 6 mm. The bed porosity of each group is ranging from 39 ~ 57 %, 32 ~ 39 % and 34 ~ 42 % respective to Al_2O_3 , ZrO_2 and SS particles. The nozzle diameter of each group used for particle sedimentation was ranging from 20 ~ 40 mm. The current experimental data of the three groups were then used as the basis of the regression analysis to correlate the dimensionless groups into an empirical correlation equation.

3.2 Development of empirical correlation

In connection to the experimental observations of H_b variation as discussed in the present study, a few experimental and model-based studies have been conducted in the past on debris bed formation characteristics considering, early phase of (melt jet) liquid stream fragmentation progression due to hydrodynamic consideration (Harvey, 2008); gradual melt release in an initially subcooled water (Yakush, 2011); gravity driven discharge of corium melt of binary oxide mixtures at different superheat temperatures (Karbojian, 2009). Their findings may not be directly applicable to the current experiments since in the current system particle bed formation phenomena are far from gradual melt release, jet break up and fragmentation scenario. Noting this distinct difference, attention was focused on previous literatures regarding the analysis of particle bed formation due to sedimentation of solid particles in quiescent fluid. In this research domain, few researchers (Sudha, 2011, Alvarez, 1982) experimentally studied the heap formation phenomenon of Gaussian-shaped bed considering the copper and lead as the

sediment particles. In their studies, sedimentation behavior of solid particles was observed to have a strong influence on repose angle.

Although in the current study, the mound shape of all the particle bed was not found alike to the typical Gaussian-shaped mound as considered by other researchers, however, the general feature of particle sedimentation and bed formation mechanism can essentially be analogous as a result of the common interaction forces such as drag force, buoyancy, gravity and particle collisions, which affecting the settling particles. Consequently, considering the philosophic views of the past experimental observations in a commensurate manner, their modeling methods might be transferable. Keeping all these in mind, based on the current experimental data an empirical correlation of the following form is proposed to estimate H_b . In the present empirical correlation we selected H_b as an indicator of the bed shape. This is because the case of coolability of debris bed, however, contingent upon a number of parameters, including bed's height H_b (Dinh, 2008, Park, 2013, Yakush, 2009, Yakush, 2009). The main intention of developing the current empirical correlation is to check its applicability for predicting the H_b of the particle bed under present experimental conditions.

Therefore, the dimensionless form of the functional relationship of Eq. (3-1) in the case of particle sedimentation phenomenon can be written as follows:

$$\frac{H_b}{D_c} = f \left(\frac{d_p}{D_c}, \frac{d_n}{D_c}, \frac{H_n}{d_n}, \frac{\Delta\rho}{\rho_p}, \frac{\varepsilon V_p}{D_c^3}, \frac{\rho_p d_n v_t}{\mu_f}, \frac{v_i}{v_t} \right) \quad (3-2)$$

The inclusion of the particle sphericity term ϕ transforms Eq. (3-2) into the following form:

$$\frac{H_b}{D_c} = f \left(\phi, \frac{d_p}{D_c}, \frac{d_n}{D_c}, \frac{H_n}{d_n}, \frac{\Delta\rho}{\rho_p}, \frac{\varepsilon V_p}{D_c^3}, \frac{\rho_p d_n v_t}{\mu_f}, \frac{v_i}{v_t} \right) \quad (3-3)$$

The left hand side of Eq. (3-3) contains a term of bed height-to-the cylinder diameter ratio, which indicates the geometrical similarity. On the right hand side of

this equation, the first term points out particle shape, the second term, third term and fourth term individually indicates the characteristic dimensional similarity, the fifth term signifies the buoyancy effect, and the sixth term indicates volumetric similarity, the seventh term implies the Reynolds number of particle jet, which is presented by the particle terminal velocity, and the last term signifies the strength of motion of the settling particles.

The above functional relationship, represented by Eq. (3-3), can be rewritten by correlating the dimensionless groups in the following form:

$$\frac{H_b}{D_c} = k(\varphi)^a \left(\frac{d_p}{D_c}\right)^b \left(\frac{d_n}{D_c}\right)^c \left(\frac{H_n}{d_n}\right)^d \left(\frac{\Delta\rho}{\rho_p}\right)^e \left(\frac{\varepsilon V_p}{D_c^3}\right)^f \left(\frac{\rho_p d_n v_t}{\mu_f}\right)^g \left(\frac{v_i}{v_t}\right)^h \quad (3-4)$$

where k is the coefficient and $a \sim h$ are the respective exponents of the system variables. We can proceed to establish dimensionless correlation by first taking the logarithms on both sides of Eq. (3-4) to result in a multiple linear regression model. The logarithmic equivalent of Eq. (3-4) is

$$\begin{aligned} \ln\left(\frac{H_b}{D_c}\right) = & \ln k + a \ln \varphi + b \ln\left(\frac{d_p}{D_c}\right) + c \ln\left(\frac{d_n}{D_c}\right) + d \ln\left(\frac{H_n}{d_n}\right) + e \ln\left(\frac{\Delta\rho}{\rho_p}\right) + f \ln\left(\frac{\varepsilon V_p}{D_c^3}\right) \\ & + g \ln\left(\frac{\rho_p d_n v_t}{\mu_f}\right) + h \ln\left(\frac{v_i}{v_t}\right) \end{aligned} \quad (3-5)$$

By performing regression analysis of Eq. (3-5) for the present experimental data, the constants (k and $a \sim h$) could be evaluated and the following dimensionless correlations can be obtained:

$$\begin{aligned} \ln\left(\frac{H_b}{D_c}\right) = & -1.585 - 0.425 \ln \varphi - 0.103 \ln\left(\frac{d_p}{D_c}\right) - 0.407 \ln\left(\frac{d_n}{D_c}\right) - 0.161 \ln\left(\frac{H_n}{d_n}\right) - 0.585 \ln\left(\frac{\Delta\rho}{\rho_p}\right) \\ & + 0.456 \ln\left(\frac{\varepsilon V_p}{D_c^3}\right) + 0.035 \ln\left(\frac{\rho_p d_n v_t}{\mu_f}\right) - 0.137 \ln\left(\frac{v_i}{v_t}\right) \end{aligned} \quad (3-6)$$

The exponential equivalence of Eq. (3-6) can be written as

$$\begin{aligned} \frac{H_b}{D_c} = & 0.2049 \varphi^{-0.425} \left(\frac{d_p}{D_c}\right)^{-0.103} \left(\frac{d_n}{D_c}\right)^{-0.407} \left(\frac{H_n}{d_n}\right)^{-0.161} \left(\frac{\Delta\rho}{\rho_p}\right)^{-0.585} \left(\frac{\varepsilon V_p}{D_c^3}\right)^{0.456} \left(\frac{\rho_p d_n v_t}{\mu_f}\right)^{0.035} \\ & \times \left(\frac{v_i}{v_t}\right)^{-0.137} \end{aligned} \quad (3-7)$$

Currently, the correlation coefficient of Eq. (3-7) is 0.96, which indicates relatively strong correlation on H_b/D_c among the eight dimensionless groups. It should be noted that Eq. (3-7) is obtained for the two-phase system, where water was used as liquid phase in a cylindrical pool with diameter of 375 mm. The empirical correlation of Eq. (3-7) has the parametric ranges as given bellow

$$\begin{aligned}
1.14 \leq d_p \leq 6 \text{ mm} & \quad 3600 \leq \rho_p \leq 7800 \text{ kg/m}^3 \\
20 \leq d_n \leq 40 \text{ mm} & \quad 473 \leq H_n \leq 720 \text{ mm} \\
46.3 \times 10^{-2} \leq v_i \leq 94.8 \times 10^{-2} \text{ m/s} & \quad 79.2 \times 10^{-3} \leq v_t \leq 110.3 \times 10^{-2} \text{ m/s} \\
32 \leq \varepsilon \leq 57 \% & \quad \mu_f = 8.91 \times 10^{-4} \text{ Pa}\cdot\text{s}
\end{aligned}$$

The corresponding ranges of dimensionless groups can also be given for further application scope of Eq. (3-7) as follows:

$$\begin{aligned}
30.4 \times 10^{-4} \leq \frac{d_p}{D_c} \leq 1.6 \times 10^{-2} & \quad 5.33 \times 10^{-2} \leq \frac{d_n}{D_c} \leq 1.07 \times 10^{-1} \\
11.83 \leq \frac{H_n}{d_n} \leq 36 & \quad 7.23 \times 10^{-1} \leq \frac{\Delta \rho}{\rho_p} \leq 8.72 \times 10^{-1} \\
30.34 \times 10^{-3} \leq \frac{\varepsilon V_p}{D_c^3} \leq 53.57 \times 10^{-3} & \quad 64 \times 10^2 \leq \frac{\rho_p d_n v_t}{\mu_f} \leq 386.24 \times 10^3 \\
8.19 \times 10^{-1} \leq \frac{v_i}{v_t} \leq 9.39 \times 10^1 & \quad 1 \leq \varphi \leq 0.4
\end{aligned}$$

3.3 Analysis and discussion of predicted and experimental results

In the comparative evaluation between the predicted and experimental results, H_b was considered as an important indicator of the bed shape owing to the coolability concern of the debris bed (Dinh, 2008, Park, 2013, Yakush, 2009, Yakush, 2009). The predicted results were compared with the experimental data based on the effects of the four crucial factors, d_n , ρ_p , d_p , and H_n concerning the change of H_b of the particle bed.

3.3.1 Accuracy of regression analysis

The regression model of the dimensionless groups is expressed by the empirical correlation presented by Eq. (3-7). The coefficient of determination (R^2) of the present regression model was found to be 0.92, which indicates that 92 percent of the original uncertainty has been explained by the present linear model. It is an indicative of the level of explained variability in the model to assess how well this model will explain and predict future outcomes. The RMS error of the empirical correlation, Eq. (3-7), was found to be 4.5 mm, which reasonably indicates a fair agreement between the predicted and experimental results. The predicted results of H_b was estimated by using the proposed empirical correlation of Eq. (3-7), and subsequently compared with the 117 experimental cases to evaluate the variation in predictions. The extent of the quantitative correlation between the predicted and experimental H_b is presented in **Fig. 3-2**. In this detailed comparison, the minimum and the maximum deviation were found to be 0.02% and -17.4%, respectively. The regression line that best fits the experimental and the predicted data of H_b is presented by the blue line with 99% confidence intervals as indicated by the green lines. Currently, the regression line follows a second order polynomial. The prediction interval of the bed heights is indicated by the red lines with 99% confidence level. This confidence interval indicates that all the predicted bed heights exist within this interval with an exception of one data point (Fig. 3-2). Nevertheless, it is noticed that relatively larger deviations tend to more fluctuating in the case of non-spherical particles. This might be due to the inadequate consideration of particle-particle frictional drag in the case of non-spherical particles.

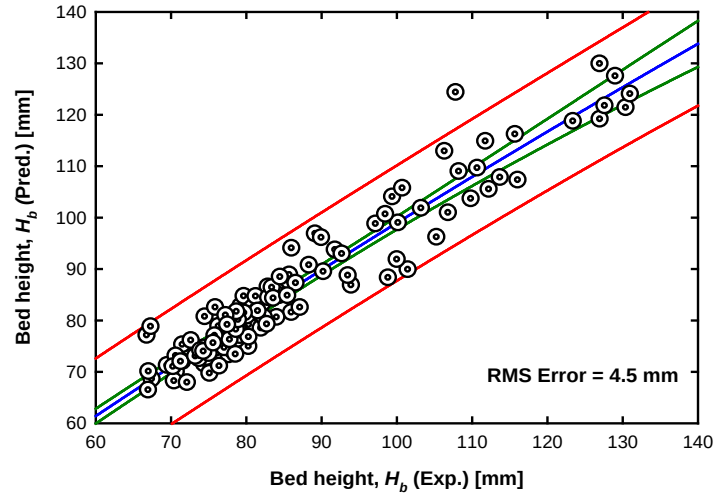
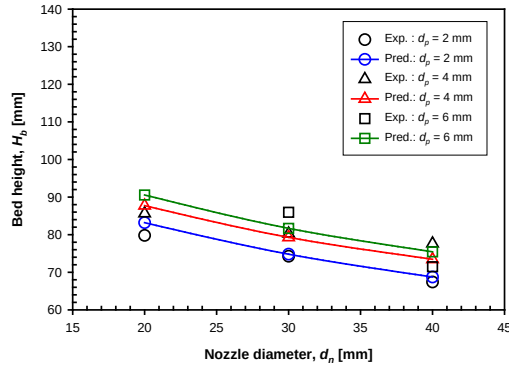


Fig. 3-2 Comparison of experimental and predicted H_b for Eq. (3-7).

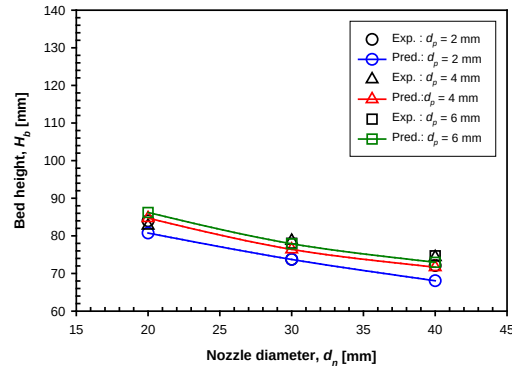
3.3.2 Effect of nozzle diameter

Fig. 3-3 shows the effect of nozzle diameter on H_b both in experiments and predictions. This figure evaluates the tendency of H_b variation in a comparative manner between the predicted and the experimental results based on changing the role of nozzle diameter for the spherical and non-spherical particles in the cases of Al_2O_3 , ZrO_2 and SS materials. From this figure a general descending trend of H_b with increased nozzle diameter is seen indicating an acceptable agreement between the predictions and the experiments for both spherical and non-spherical particles in the cases of respective nozzle height. The reason of the descending trend of H_b with increased nozzle diameter is mainly due to the increasing effect of the impact force on the mound top causes by the wide particle jet for larger nozzle diameter. A relatively good agreement was observed in the cases of spherical particles than that of non-spherical ones, Figs. 3-3 (a) to (e). In the case of non-spherical Al_2O_3 particles the predicted H_b was found relatively underestimated when $d_p > 2$ mm with $d_n = 20$ and 30 mm in Fig. 3-3 (d), whereas for non-spherical SS particles with $d_p = 1.14$ mm, a similar underestimation was observed for all the nozzles in Fig. 3-3 (e). This

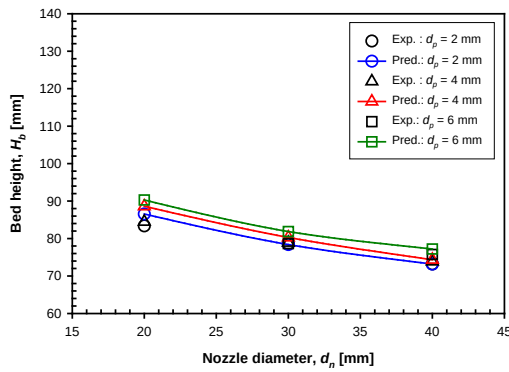
underestimation might be due to an inadequate consideration of particle-particle frictional drag effect. However, the proposed empirical correlation can reasonably reproduce the nozzle size effect in the overall trend of H_b variation.



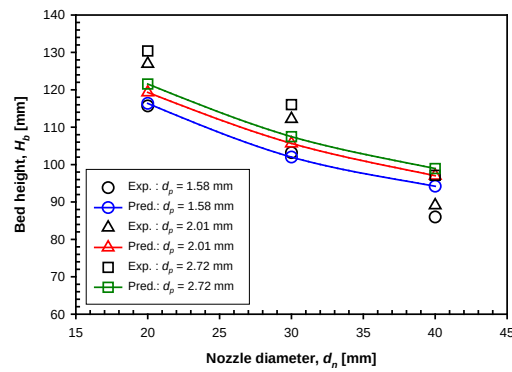
(a) Spherical Al_2O_3 ; $H_n = 720$ mm



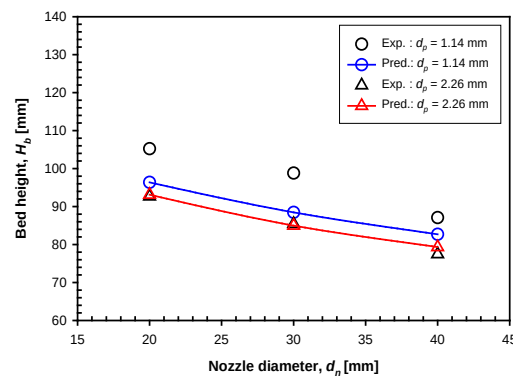
(b) Spherical ZrO_2 ; $H_n = 630$ mm



(c) Spherical SS; $H_n = 473$ mm



(d) Non-spherical Al_2O_3 ; $H_n = 720$ mm

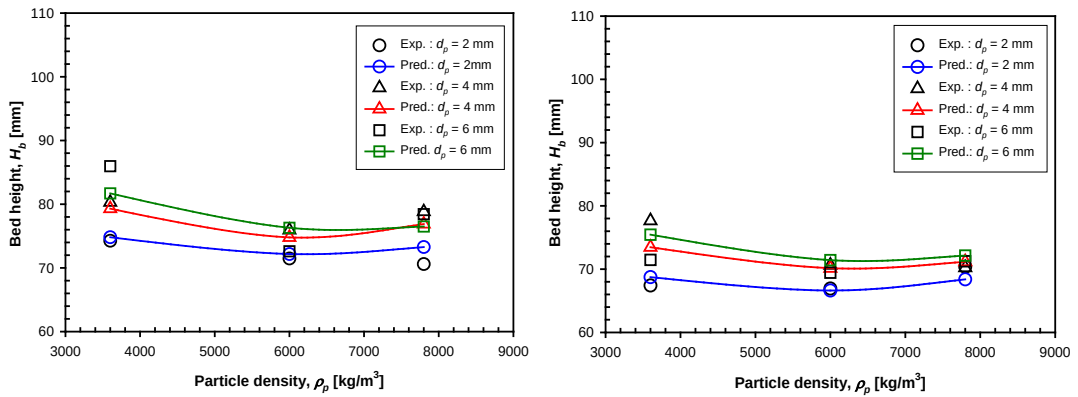


(e) Non-spherical SS particles; $H_n = 473$ mm

Fig. 3-3 Comparison of H_b variation with nozzle diameter between experiments and predictions for spherical and non-spherical particles.

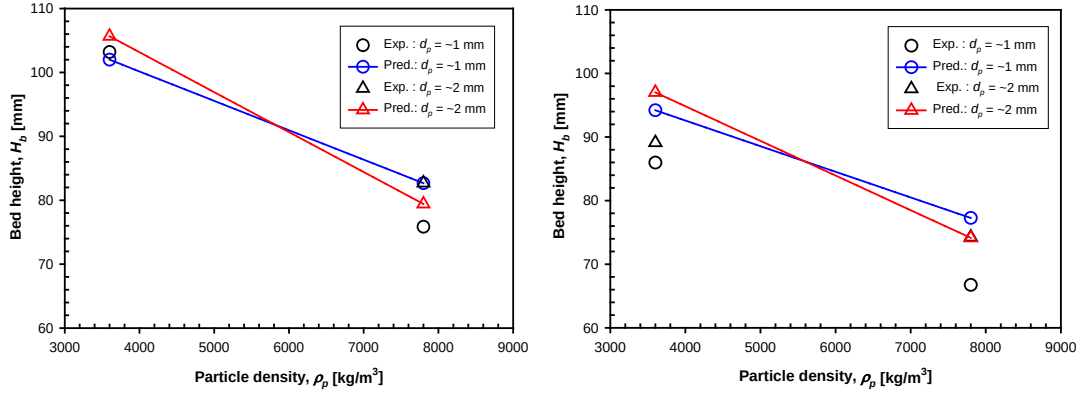
3.3.3 Effect of particle density

Fig. 3-4 illustrates the effect of particle density on H_b . This figure evaluates the degree of variation in the predicted H_b based the experiments when the particle density acts as a crucial factor. From this figure a descending trend of H_b with a small dependency on the increased density is seen for the spherical particle both in the cases of $d_n = 30$ and 40 mm, as shown in Fig. 3-4 (a) and (b). In the case of spherical particle the descending trend of H_b does not remarkably exist particularly with density 7800 kg/m³. This is mainly due to the reason that the impact force of the particle jet is not large enough to disperse the relatively heavier particles. A larger descent in the trend of H_b variation is seen for the non-spherical particles in comparison of the spherical ones for both the cases of $d_n = 30$ and 40 mm, as shown in Fig. 3-4 (c) and (d). Currently, the proposed empirical correlation reasonably reproduces the descending trend of H_b for both the cases of spherical and non-spherical particles with $d_n = 30$ and 40 mm, although some differences between the experimental and predicted results are still evident.



(a) $d_n = 30$ mm (spherical particles)

(b) $d_n = 40$ mm (spherical particles)



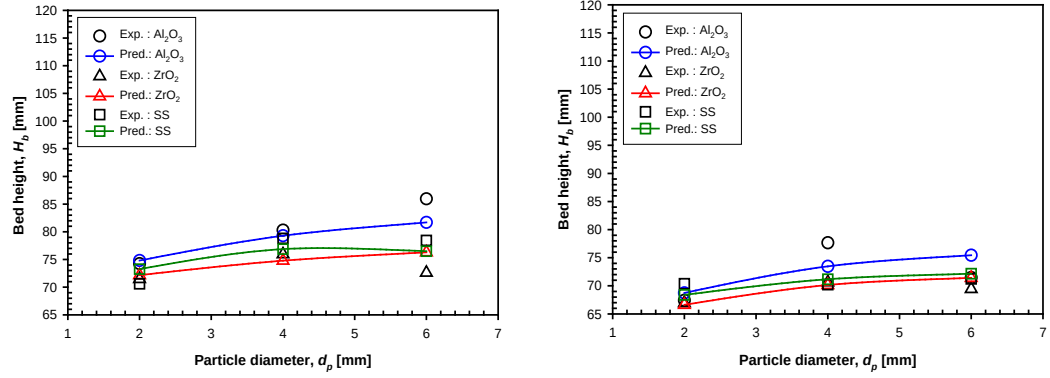
(c) $d_n = 30$ mm (non-spherical particles) (d) $d_n = 40$ mm (non-spherical particles)

Fig. 3-4 Comparison of H_b variation with particle density between experiments and predictions for spherical and non-spherical particles ($H_n = 720$ mm).

3.3.4 Effect of particle diameter

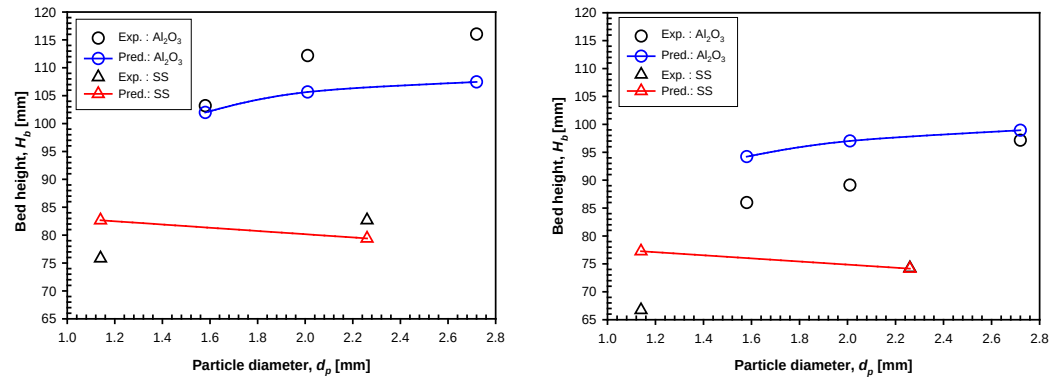
Fig. 3-5 shows the effect of the particle diameter on H_b . The experimental results of H_b are generally reproduced well by the predictions, indicating a fair agreement for both the spherical and non-spherical particles, as shown in Fig. 3-5 (a) to (d). Fig. 3-5 (a) shows a gradual increasing trend of H_b both in experiments and predictions indicating a gradual dependency on the particle size in the case of $d_n = 30$ mm. From this figure we can see relatively large deviation of the predicted H_b with experiments in the case of $d_p = 6$ mm for the particles except SS with $d_n = 30$ mm. In the case of $d_n = 40$ mm with spherical particles the predicted ascending trend of H_b deviates with experiments mainly for $d_p = 6$ mm of Al_2O_3 and ZrO_2 particles, although the difference is relatively small, as shown Fig. 3-5 (b). In the case of non-spherical particles, the general trend of the predicted H_b variation is found almost in a similar fashion of the experiments both in the cases of $d_n = 30$ and 40 mm for Al_2O_3 particles, as shown in Fig. 3-5 (c) and (d). On the other hand, the predicted trend of H_b variation in the case of non-spherical SS particles exhibits a deviation mainly with $d_p = 1.14$ mm, indicating some difference both in the cases of $d_n = 30$

and 40 mm, as shown in Fig. 3-5 (c) and (d). Nevertheless, this difference of the predicted H_b is rather small in comparison to the magnitude of experimental results.



(a) $d_n = 30$ mm (spherical particles)

(b) $d_n = 40$ mm (spherical particles)



(c) $d_n = 30$ mm (non-spherical particles) (d) $d_n = 40$ mm (non-spherical particles)

Fig. 3-5 Comparison of H_b variation with particle diameter between experiments and predictions for spherical and non-spherical particle ($H_n = 720$ mm).

3.3.5 Effect of nozzle height

Fig. 3-6 presents the effect of nozzle height variation on H_b . The general descending trend of the predicted H_b variation is found almost in a similar fashion of the experiments for both the spherical and non-spherical particles with $d_n = 30$ and 40 mm, as shown in Fig. 3-6 (a) to (d). The reason of this descending trend is mainly due to the increasing effect of the impact force of particle jet for the subsequent increment of particle velocity as a result of raising the nozzle height. In the

comparative evaluation with H_n variation, the predicted H_b indicates a larger difference with the experiments in the case of non-spherical particles for both $d_n = 30$ and 40 mm. In general, H_b was found relatively underestimated for $H_n = 473$ mm, whereas it was overestimated for $H_n = 720$ mm in the cases of both spherical and non-spherical particles as can be seen in Fig. 3-6. At the same H_n , relatively large elevation of H_b was observed in the case of non-spherical particles than that of the spherical ones, even with the larger spherical particles both with $d_n = 30$ and 40 mm.

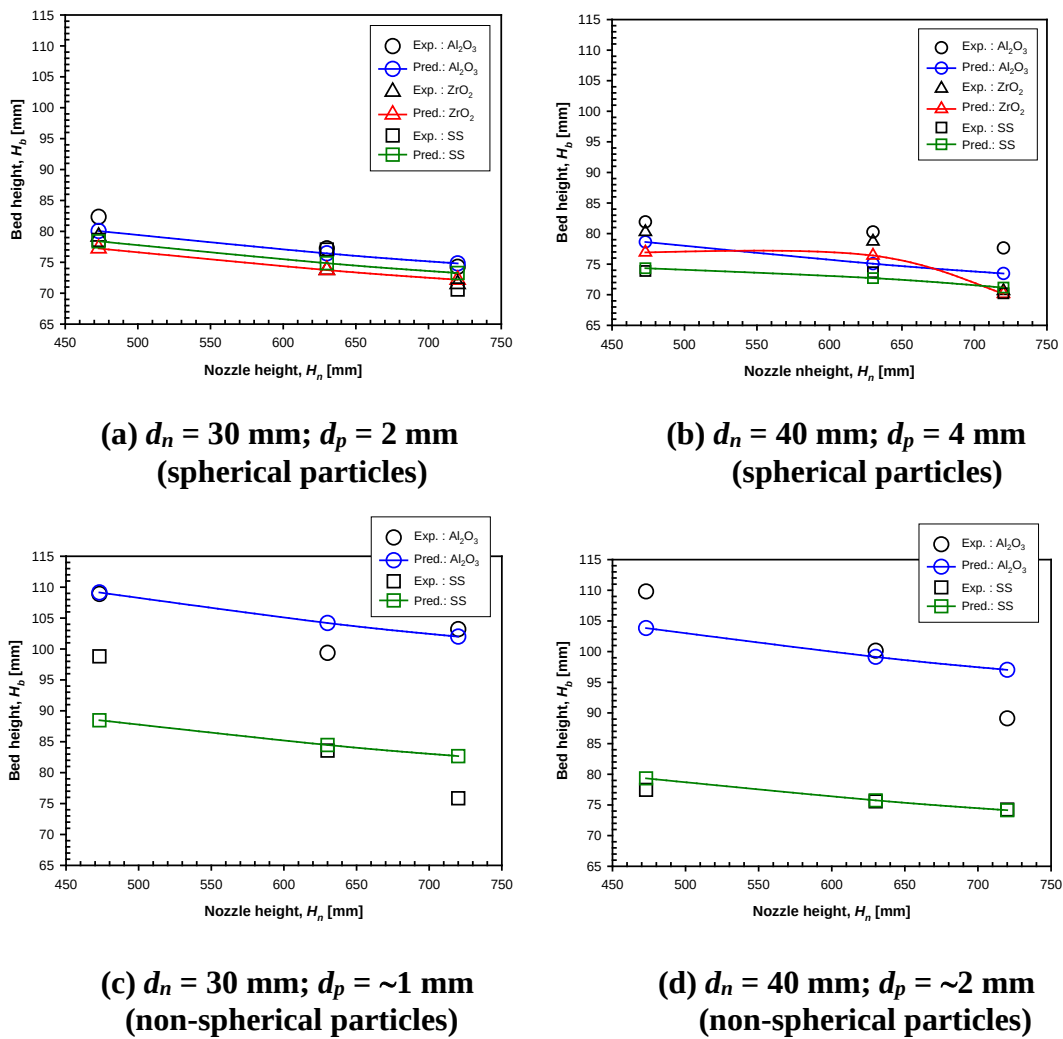


Fig. 3-6 Comparison of H_b variation with nozzle height between experiments and predictions for spherical and non-spherical particles.

3.4 Summary and concluding remarks

In comparison of the experiments, the variations in the predictions were investigated to check the reliability of the H_b estimation by the proposed empirical correlation. The predicted H_b reasonably demonstrates the effects of the four crucial factors in a similar manner of the experiments indicating small differences between the experimental and predicted results. A relatively small RMS error indicates that the reasonable accuracy of the developed empirical correlation, presented by Eq. (3-7), rationally reproduce the experimental H_b indicating relatively strong correlation with the predicted results. It can be summarized that the current empirical correlation demonstrates its fundamental applicability for reasonable estimation of H_b in the case of sediment particle bed under the present experimental conditions. Therefore, the proposed empirical correlation can logically be useful to find out which parameters have sensitive role on developing a flatten shaped particle bed.

Chapter 4

NUMERICAL SIMULATIONS OF PARTICLE SEDIMENTATION BY DEM

The current analyses were conducted in order to simulate the sedimentation behavior of solid particles onto a particle collector plate in isothermal condition at room temperature. In the present study, the validation and verification of DEM based models and simulation codes were performed based on the results of spherical particle sedimentation experiments. A detailed description of the modeled experimental geometry is given in Chapter 2 as well as a brief outline of the experimental conditions and simulated cases are presented in Chapter 4. The simulation results were compared with experimental results to determine the basic applicability of DEM based simulation techniques for the investigation of particle sedimentation behaviour owing to its significance on the coolability of debris bed in CDAs. The main purpose of this study is to compare the present model predictions with experimental observations to find out which parameters are most dominant, to help us better understand the sedimentation mechanism.

4.1 Introduction

In the event of a CDA in SFRs the melt can descend rapidly into the sodium-filled area at the lower plenum of the reactor vessel because of gravity-driven discharge of molten core materials through relocation paths. It is well acknowledged that in the course of melt relocation in a SFR, melt–sodium contact leads to solidification and fragmentation of molten core materials with very small particles. Such fragmentation may increase the lateral spreading of the fragmented core

materials once the materials have moved into more open areas (Tentner, 2010). This lateral spreading is likely to have an impact on the debris sedimentation behavior while forming a debris bed onto the core-support structure or the debris tray. Investigation on such lateral sedimentation behavior of fragmented debris can significantly promote the characteristic evaluation of the debris bed shape. To mitigate the recriticality concern in CDA, redistribution of molten core materials and the subsequent sedimentation of the fragmented debris on the core catcher plate is crucial for the secured in vessel retention (Shudha, 2011). Such sedimentation behavior can be evaluated experimentally with a limited scope of reproducibility because of the high cost and prolonged duration of the process. Even if we overcome the high cost and long duration of such an experiment, the reactor conditions cannot be fully reproduced. In addition, reasonable extrapolation to reactor conditions would be difficult based only on experimental data. These limitations exhibit the necessity of numerical investigation on sedimentation behavior using solid particles as simulated debris. In the present study, particle sedimentation behavior and bed formation characteristics were modeled to investigate the particle settling behavior in a liquid medium. In the present study, the particulate phase was modeled using the Lagrangian approach based on the discrete element method (DEM) (Cundall, 1979), where interactions due to collisions among the particles can be taken into account.

To understand the particle sedimentation and its evolution during the settling process, different semi-dynamic numerical models such as the sticking model (Tassopoulos, 1989), discrete stochastic model (Houi, 1986), and kinetic force–balance model (Lu, 1993) can be used. As the inter-particle forces in these models are either ignored or treated based on assumptions, these models might be inappropriate to study the effects of the forces on bed formation during particle

sedimentation process. On the other hand, models based on the DEM (Yu, 2004) are fully dynamic, describing the motion of individual particles and explicitly considering the interactions among particles. DEM has been proved to be a useful technique to study the packing and flow of particles (Yang, 2000; Yang, 2003), which is similar to particle settling in a fluid. For granular materials, for example, the particle properties and interaction laws are implemented into DEM, which can simulate the collective behavior of the dissipative many-particle system (Luding, 2008). A few attempts have been made to apply the DEM approach to model the processes of particle sedimentation in a liquid phase. In the present study, we apply a two-dimensional DEM model to simulate the sedimentation of solid particles in liquid. In this work, we improve the DEM model by optimizing the DEM parameters to make the calculation process more efficient yet maintain reasonable precision. One of the aims of the present study is to demonstrate the fundamental applicability of the proposed simulation model to some basic characteristics of sedimentation behaviors with spherical particles. The main purpose of this study is to compare the DEM model predictions with experimental observations to find out which parameters are most dominant, to help us better understand the sedimentation mechanism.

4.2 Numerical model

In a DEM simulation, a particle's translational and rotational motion can be described by Newton's second law of motion (Dong, 2009), given by

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{F}_i \quad (4-1)$$

and

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \mathbf{T}_i \quad (4-2)$$

where $\mathbf{v}_i$, $\boldsymbol{\omega}_i$, m_i and I_i are the translational and angular velocities, mass, and moment of inertial of particle i , respectively; and $\mathbf{F}_i$ and $\mathbf{T}_i$ are the total force and torque acting on particle i , respectively, as shown in **Fig. 4-1**.

Here, the total force and torque are given by

$$\mathbf{F}_i = \sum_j (\mathbf{F}_{ij}^n + \mathbf{F}_{ij}^s) + \mathbf{F}_{\text{buoy},i} + \mathbf{F}_{\text{drag},i} + \mathbf{F}_{g,i} \quad (4-3)$$

$$\mathbf{T}_i = \sum_j (\mathbf{R}_i \times \mathbf{F}_{ij}^s - \mathbf{T}_{ij}^r) \quad (4-4)$$

where $\mathbf{F}_{ij}^n$ and $\mathbf{F}_{ij}^s$ are the normal and tangential contact forces between particles i and j , respectively; $\mathbf{F}_{\text{buoy},i}$, $\mathbf{F}_{\text{drag},i}$ and, $\mathbf{F}_{g,i}$ are the buoyancy and the drag forces, and the gravity acting on particle i , respectively. $\mathbf{T}_{ij}^r$ is the torque caused by the rolling friction due to the elastic hysteresis losses or viscous dissipation between colliding particles i and j (Brilliantov, 1998, Zhou, 1999) and $\mathbf{R}_i$ is the radius of particle i .

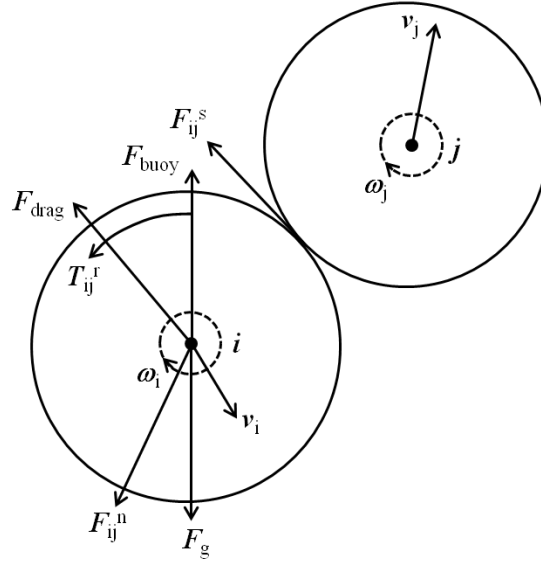


Fig. 4-1 Illustration of the forces acting on particle i .

The particles are simulated using the linear contact model (Hu, 2010). There is a range of available contact force models that approximate the collision dynamics to various extents. A conventional linear spring–dashpot model is used in our

simulations. The contact forces among the solid spherical particles in the normal and tangential directions at the contact points can be given as

$$\mathbf{F}_{ij}^n = -k_n \delta_n - c_n \frac{d\delta_n}{dt} \quad (4-5)$$

$$\mathbf{F}_{ij}^s = \min \left(\left| k_s \delta_s + c_s \frac{d\delta_s}{dt} \right|, \mu \mathbf{F}_n \right) \text{SIGN} \left(k_s \delta_s + c_s \frac{d\delta_s}{dt} \right) \quad (4-6)$$

where $\mathbf{F}$ is the contact force, δ is the relative displacement of particles i and j at the contact point; k , c and μ are the stiffness, damping and friction coefficients, respectively, and subscripts n and s represent the normal and tangential directions, respectively. **Fig. 4-2** shows the collisional force model used here.

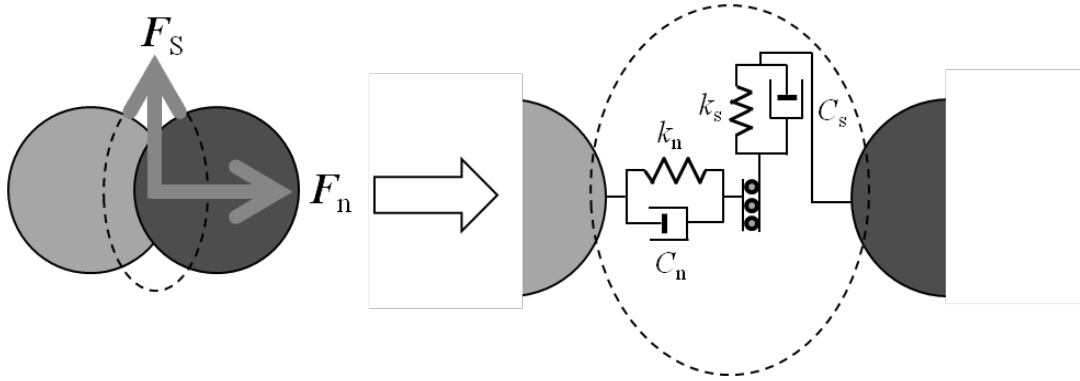


Fig. 4-2 Illustration of the contact force model.

In this work, we rewrite the normal stiffness coefficient k_n and damping coefficient c_n in the following forms:

$$k_n = \frac{4\pi^2 m^*}{(\alpha_{t_n} \Delta t)^2} \quad (4-7)$$

$$c_n = 2\alpha_{c_n} \sqrt{m^* k_n} \quad (4-8)$$

where m^* is the equivalent mass of particle i and j, given by $m^* = \frac{m_i m_j}{m_i + m_j}$, α_{t_n}

and α_{c_n} are the dimensionless stiffness and damping correlation constants, respectively, and Δt is the time step size, which should satisfy a criterion of critical

time step size $\Delta t \leq \Delta t_c (= 2\sqrt{m^*/k_n})$ (Cundall, 1979). The time step size essentially controls the accuracy of this DEM calculation.

The stiffness and damping correlation constants as well as the time step size are chosen as input DEM parameters and are optimized based on reference experimental data. Initially, Δt was determined by considering the balance between the accuracy and efficiency of the numerical calculation to obtain a reasonable result, and was found to be 1.0×10^{-6} s under the present experimental conditions. This value of Δt was obtained so that the physical disturbance of local interactions cannot propagate from any particle to the others except its immediate neighbors. As a result, collisional interactions of any particle are always limited to the several neighboring particles. The time step size Δt was then determined by using the relation $\Delta t = \Delta t_c / \alpha_{t_n}$.

The stiffness correlation constant α_{t_n} was determined by a conventional numerical test of a free-falling elastic particle bouncing onto a solid horizontal plane. Its appropriate value was found to be 300 under the present experimental conditions. To determine the value of the damping correlation constant α_{c_n} we investigated the overlapping behavior between particles in test runs of particle sedimentation simulation by following a criterion that required the overlapping to be less than 1% of the particle diameter. Its value was determined to be 0.03 during the evaluation process. The tangential stiffness coefficient k_s and damping coefficient c_s can be defined from the principles of material mechanics as follows:

$$k_s = \frac{k_n}{2(1+\nu)} \quad (4-9)$$

$$c_s = \frac{c_n}{2(1+\nu)} \quad (4-10)$$

where ν is Poisson's ratio. In the present simulations, inclusion of α_{t_n} and α_{c_n} has reduced the four DEM constants (k_n , k_s , c_n , and c_s) to two, which are expressed by the mathematical relation among them through Eqs. (4-7) to (4-10). The advantage of using α_{t_n} and α_{c_n} instead of the four DEM constants as numerical variables is that it offers good scope to quantify the effect of the normal and tangential components of the force on the model predictions by varying only two values rather than four.

As well as the DEM model, the interaction features between the particles and fluid should also be incorporated. In this context, three forces—drag, buoyancy, and gravity – are considered (Zhang, 2010). They are given by

$$\mathbf{F}_{drag} = C_d \pi \left(\frac{d_p}{2} \right)^2 \frac{1}{2} \rho_p v^2 \quad (4-11)$$

$$\mathbf{F}_{buoy} = \frac{4}{3} \pi \left(\frac{d_p}{2} \right)^3 \rho_f g \quad (4-12)$$

$$\mathbf{F}_g = -\frac{4}{3} \pi \left(\frac{d_p}{2} \right)^3 \rho_p g \quad (4-13)$$

where C_d is the dimensionless drag coefficient, d_p is the particle diameter, ρ_p is the particle density, v is the particle velocity relative to fluid, and g is the gravitational acceleration. The drag coefficient is calculated using the following correlation (Clift, 1978) as a function of the Reynolds number $Re = \frac{\rho_f v d_p}{\mu_f}$:

$$C_d = 0.2924 \left(1 + 9.06 Re^{-\frac{1}{2}} \right)^2 \quad (4-14)$$

where μ_f is the fluid viscosity. This correlation is applicable in the range, $Re < 6000$.

Regarding the drag force calculation using Eq. (4-11), a one-way approach is implemented in the present simulations. This approach can potentially cause some discrepancy from experimental results because it ignores the effect of fluid convection caused by particle–fluid interactions. This simplification might be

accepted if the fluid convection will not develop enough to change the movement of relatively heavy particles largely during a short period of particle falling and settling process. Its validity will be discussed by comparison of particle sedimentation behaviors between experiments and simulations.

4.3 Simulation geometry

4.3.1 Experimental conditions

The geometry of the experimental apparatus which was modeled in the DEM based simulations of particle sedimentation experiments is shown in **Fig. 2-1**. In the experimental runs, a stopper rod with a conical end was inserted into the funnel to plug the release hole for preventing the solid particles flowing out during filling, which was not modeled in simulations for simplicity. Although in the experiments, the cylindrical vessel was placed inside an outer rectangular pool of transparent acrylic by pouring water inside the gap, however, in simulations we used only the cylindrical vessel as there was no necessity to reduce the effect of refraction. All simulation experiments were performed by gravity-driven discharge of the dry solid particles into the quiescent water pool under isothermal conditions at a room temperature. It is noted that during the particle falling process, the particle jet initiated particle–nozzle interactions, and then particle–particle and particle–fluid interactions were also caused in the water pool. The particle–nozzle interactions play a key role on deflection of the particle plume, which will augment the particle scattering in the pool. As discussed later, the effect of particle–nozzle interactions mainly depends on the particle size relative to the nozzle size.

In the experiments, we focused our attention on the effects of three crucial factors: ρ_p , d_p , and d_n , and found that the particle sedimentation characteristic as well

as the deposited particle bed shape can change based on the effects of these factors. In addition, variations in the particle sedimentation patterns in the water pool were observed when different values of ρ_p , d_p , and d_n were used. The experiments and simulations were designed to investigate the effects of these three factors based on the significant role they play in the particle sedimentation process as observed in our previous experimental study. The variation of the physical parameters used in the simulations is listed in **Table 4-1**.

Table 4-1 Parameter variation in the simulated cases

Run No.	Nozzle diameter, d_n (mm)	Particle diameter, d_p (mm)	Particle density, ρ_p (kg/m ³)
1	20	2	3,600 (Al ₂ O ₃)
2	30	2	
3	40	2	
4	20	4	
5	30	4	
6	40	4	
7	30	6	
8	40	6	
9	20	2	6,000 (ZrO ₂)
10	30	2	
11	40	2	
12	20	4	
13	30	4	
14	40	4	
15	30	6	
16	40	6	
17	20	2	7,800 (SS)
18	30	2	
19	40	2	
20	20	4	
21	30	4	
22	40	4	
23	30	6	
24	40	6	

In the simulations, different combinations of parameter values were assigned as inputs to evaluate their effect on particle sedimentation behavior in terms of the three key quantitative parameters. Unless otherwise stated, when studying the effect of a parameter, only this parameter is varied while the others are fixed at their base values. The base value and the varying range of the parameters used in the simulations are listed in **Table 4-2**. The simulation cases shown in Table 4-2 were selected from the experimental ones to cover typical ranges of experimental conditions.

Table 4-2 Parameters used in the simulations

Parameter	Base value and varying range
Particle number, N	469 – 4,244
Poisson's ratio, ν	0.27
Stiffness correlation constant, α_{t_n}	300
Damping correlation constant, α_{c_n}	0.03
Time step size, Δt	1.0×10^{-6} s
Friction coefficient, μ	0.3
Fluid density, ρ_f	997 kg/m ³
Fluid viscosity, μ_f	8.91×10^{-4} Pa·s

Difference and similarity in conditions between the present experiments and the PAMR phase of SFRs are discussed based on physical properties of debris and coolant, and debris relocation path. **Table 4-3** shows the comparison of the reactor accident and experimental conditions.

In accident conditions, the debris, which are the fragmented core materials, consist of the mixture of stainless steel (SS) and MOX fuel, while we used the solid particles of Al₂O₃, ZrO₂ and SS as simulant debris. SS is one of the actual debris

components, and its large density is smaller than, but comparable with fuel one. In general, the debris, which are formed due to fuel-coolant interactions (FCIs), are very fine, and their typical size would be in the range of 0.1 ~ several millimeters (Gluekler, 1977). Although the smallest particles used in the experiments are relatively larger than the average debris size, the experimental condition of particle size overlaps variations of the actual debris size. The particle shape will dominate the particle sedimentation behaviors, and hence the effect of particle sphericity should be investigated extendedly based on knowledge on fundamental characteristics of sedimentation behaviors obtained from the present study for spherical particles. Although, in the experiments, water was used as simulant coolant, its density is similar to sodium, and water and sodium have the same order of magnitude in viscosity.

In the PAMR phase of SFRs, it is considered that one of the typical melt relocation paths from the disrupted core to the lower plenum is the control rod guide tube (CRGT), which has relatively large potential of fuel removal from the core because of its large hydraulic diameter about ~ 10 cm (Tentner, 2010). After the melt discharge to the plenum, FCIs lead to solidification and fragmentation of the melt with very small particles. To investigate FCI phenomena, in fact, a lot of out-of-pile experiments have been performed by discharging the melt into the coolant as a jet through a circular nozzle with a diameter of several centimeters (Bank, 2003, Karbojian, 2009). The fragmented core materials into fine debris will relocate to the bottom of the reactor vessel or to the core-catcher (debris tray) finally. Therefore, the discharge of simulant debris through a circular nozzle, as shown in Fig. 2-1, is a reasonably simplified experimental methodology to investigate the fundamental characteristics of debris sedimentation behaviors. The debris will settle in the plenum

by gravity over a height of about 1 ~ 2 m, which depends on the reactor design and fragmentation process. Therefore, the nozzle size and the nozzle height from the debris tray in the present experiments are comparable with reactor conditions.

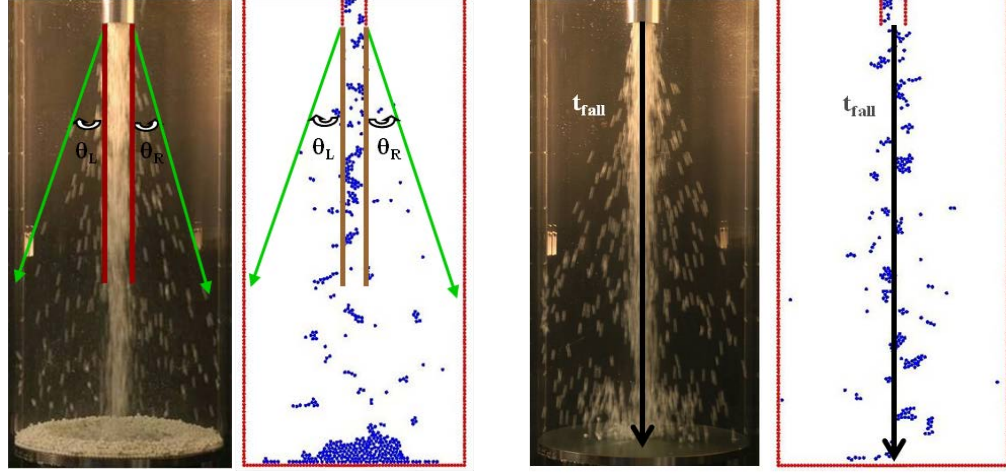
Table 4-3 Comparison of reactor accident and experimental conditions

Physical quantities	Conditions	
	Reactor accidents	Experiments
Debris	Mixture of SS and MOX fuel	Al ₂ O ₃ , ZrO ₂ and SS
Density	7,620 kg/m ³ (SS) ~ 10,800 kg/m ³ (MOX fuel) at 1000 K	3,600 kg/m ³ (Al ₂ O ₃) 6,000 kg/m ³ (ZrO ₂) and 7,800 kg/m ³ (SS) at 298 K
Diameter	0.1 ~ several millimeters	1.14 ~ 6 mm
Shape	non-spherical particles	spherical and non-spherical particles
Fluid (coolant)	sodium	water
Density	830 kg/m ³	997 kg/m ³
Viscosity	2.40×10 ⁻⁴ Pa·s at 773 K	8.91×10 ⁻⁴ Pa·s at 298 K
Relocation path	CRGT (typical)	cylindrical nozzle
Diameter of debris jet	about 0.1 m	0.02, 0.03 and 0.04 m
Height of fall	about 1 ~ 2 m	0.473, 0.630 and 0.720 m

Nevertheless, in the future scope of the present experimental study it is necessary to extend the range of experimental parameters. As mentioned above, the experimental conditions were determined considering typical reactor conditions, although simplified ideal conditions were taken from the viewpoint of experimental

methodology. Of course, since the present conditions cannot cover the wide range of expected accident conditions fully, sensitivity of some parameters to results was investigated to compensate for this inadequacy in the experiments. It is noted that our experiments were performed mainly to comprehend some general characteristics of particle sedimentation behaviors, which would be involved in expected accident phenomena.

Currently, the model predictions were evaluated and compared to the experimental observations in terms of the three key quantitative parameters. Based on previous experimental observations, particle sedimentation can be characterized by particle fall behavior and bed shape. To define particle fall behavior, we recorded the particle dispersion angle and fall time in the pool. The particle dispersion angle plays an important role in determining the height and shape of the bed, which in turn can affect the coolability of the debris bed. Further, the particle fall time may vary based on the particle–fluid interaction; this affects the particle sedimentation process, which will also influence the bed shape and height. Moreover, the particle–nozzle interactions presumably impose some impact on the particle sedimentation behavior. Noting the significance of these features, we selected three key parameters to quantify the sedimentation process: the maximum particle dispersion angle (θ), the particle fall time (t_{fall}), and the bed height (H_b). The relationship of the quantitative parameters θ and t_{fall} with the particle bed height are discussed in Section 4.5.3. The evaluation process of these key quantitative parameters is illustrated in **Fig. 4-3**.



(a) Evaluation of max. dispersion angle (b) Evaluation of particle fall time



(c) Evaluation of bed height and shape

Fig. 4-3 Illustration of the three key quantitative parameters used for quantitative evaluation of particle fall and sedimentation patterns.

In the present analysis, the maximum particle dispersion angle is expressed as $\theta = \theta_L + \theta_R$, where θ_L and θ_R are the dispersion angles observed on the left and right side of the nozzle, respectively. The particle fall time is defined as the time taken by the first particle batch to travel from the end of the nozzle to the debris tray. The maximum height is defined as the bed height measured along the axis of symmetry.

It is known that the shape of solid particles severely affects the flowability and repose angle of particle materials (Lube, 2005, Oshima, 1995). Therefore, the particle sphericity will be also one of the major factors that dominate the particle sedimentation behaviors. Although the present simulation model should be applicable only to the systems of spherical particles, the conventional DEM for

spherical particles has been extended to represent the effect of particle shape on particle-particle interactions (Abbaspour-Farid, 2005, Markauskas, 2006, Jensen, 1999). In addition, it might be relatively simple to consider interactions between non-spherical particles and fluid by using effective drag coefficients for non-spherical particles. One of the purposes in the present study is to demonstrate the fundamental applicability of the proposed simulation model to some basic characteristics of sedimentation behaviors with spherical particles under some ideal conditions.

4.3.2 Simulation conditions and model geometries

In our simulations the position of each particle is assigned in the funnel with no inter-particle overlap. Next, a free-falling run of the particles within the funnel is conducted for several seconds as a pre-process of commencing particle sedimentation in the simulations. Then, gravity-driven discharge of the particles occurs and particle sedimentation commences. The particles settle on the debris tray, forming a bed, as shown in **Fig. 4-4**. In the simulations, the particle motion and sedimentation process is reproduced in 2D and this is then compared with the cross-sectional view of the particle beds in the different experiments. To investigate the sedimentation behavior in a realistic way, the 2D results need to be compared with the 3D analysis. However, the present comparisons can be useful to clarify whether some of the deviations that appear in the simulation results are generated by the 2D approach.

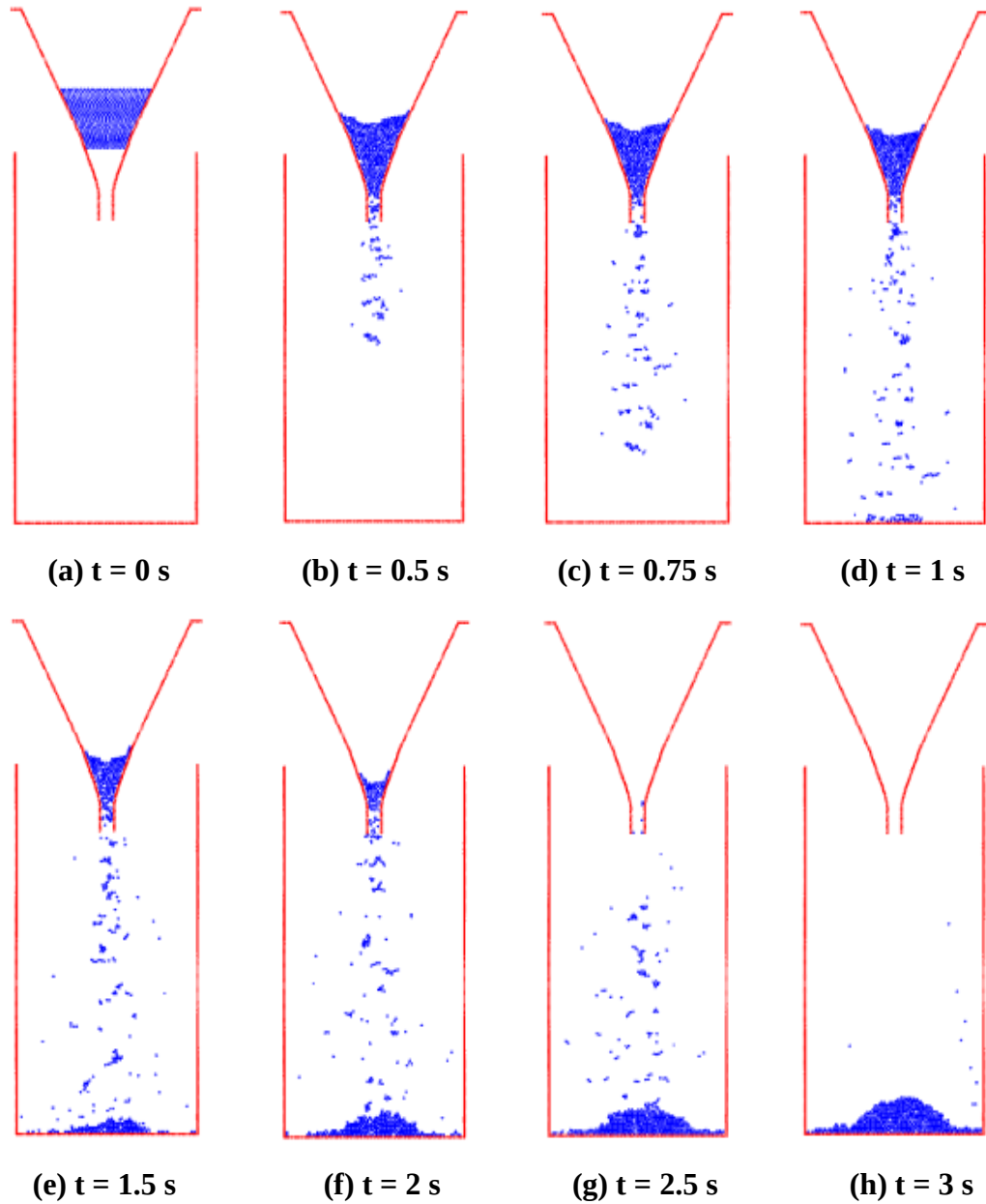


Fig. 4-4 Time-lapse shots showing particle sedimentation and particle bed formation process.

The modeled geometry of the experimental setup used in the particle sedimentation simulation is shown in **Fig. 4-5**. The acrylic vessel wall, which has little or no influence on the sedimentation process, was modeled as a material similar to that of the solid particles. The stopper rod, which prevents the solid particles from flowing out of the funnel before the start of the experiment, was not modeled in the simulation for simplicity. The simulated border geometries in Fig. 4-5 were

classified into three categories: type 1, type 2, and type 3. The purpose is to imitate the real border contours of the experimental setup. As shown in Fig. 4-5, the plane wall borders are modeled as a type 1 border geometry and the walls with concave and convex corners are modeled as type 2 and type 3 border geometries, respectively. In the present simulations, the same material properties as the solid particles were used even for the nozzle. However, this simplification might cause some deviation in particle sedimentation behaviors from the experiments. This is because during the particle settling process the particle–nozzle interactions initiate a scattering effect on the falling particles, which spread the particle plume laterally in the water pool.

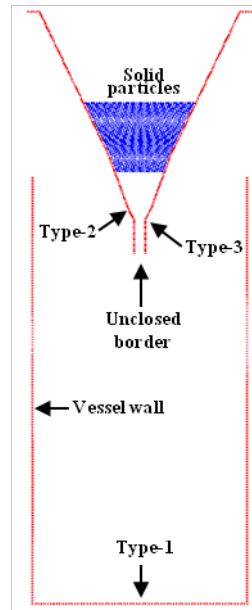


Fig. 4-5 Simulation geometry used in the present simulations.

4.4 Model parameters

In the 2D simulations, the number of solid particles was determined based on the average bed height and the bed diameter. For this purpose, we calculated the average bed height by using the formula $V_b = \pi \left(\frac{d_b}{2} \right)^2 h_b$, where V_b is the total volume of a cylindrical shaped particle bed with a volume equal to 0.005 m³ or 5 L,

h_b is the average bed height, which refers to the average height of the cylindrical bed, and d_b is the bed diameter, which is equal to the pool diameter of 0.375 m in the present experiments. After determining the average bed height, the number of particles equivalent to this bed height was calculated for each particle size. By dividing the bed height by the particle diameter, the number of particles in a single particle column is calculated. In the same manner, by dividing the pool diameter by the particle diameter, the number of particles in a single particle row is calculated.

For a 2D view, the total number of particles equivalent to the bed volume of 0.005 m^3 was obtained by multiplying the number of particles calculated for a single column by the calculated number of particles in a single row. Finally, the total number of particles in the bed volume calculated above is used in the simulations. We determined the number of particles based on a simplified model that may underestimate the total number of particles compared to a more realistic model. Regarding the validity of the 2D approach, the cross-sectional view of the particle sedimentation process generated in the simulation corresponds to a 2D image where the particles are arranged in a 2D array in the funnel. This particle arrangement was validated by comparative analysis. Other parameters used in the simulations were selected so as to best model the experimental conditions. Although the simulations did not realistically model the interaction between the vessel wall and the particles, the results of the simulations agree with the experimental observations in general, confirming the rationality of our approach regarding the particle–wall interaction.

4.5 Simulation results and discussion

To compare the simulation results with the experimental results of the particle sedimentation behavior, we investigated the effect of the crucial factors: d_p ,

ρ_p , and d_n on the sedimentation process. The particle sedimentation process was characterized by particle fall behavior and bed shape. To investigate the sedimentation process, we selected three key quantitative parameters: θ , t_{fall} , and H_b . In the simulations we examined the effect of d_p , ρ_p , and d_n on these three key quantitative parameters and compared the results with the experimental values. In addition, the bed shapes of some of the experimental and simulation runs were compared in terms of bed height variation at different points of collector plate breadth. In the simulations, spherical particles of Al_2O_3 , ZrO_2 , and SS were used to investigate the particle sedimentation pattern when passing through nozzles of different sizes.

In the quantitative analysis of particle sedimentation behavior, we focused on evaluating the particle settling characteristics in terms of the three key quantitative parameters mentioned above. The data used to evaluate these parameters were extracted from the video images of the particle sedimentation experiments using image analysis software. These quantitative evaluations were later used for the comparative analysis. The results of the comparative analysis between the simulations and the experiments are discussed in the following sections.

To evaluate our comparative analysis, the correlation coefficient between the simulated and experimental data was calculated. We determined the strength and direction of the linear relationship between the simulated and experimental results. The correlation coefficient ranged between -1.0 and $+1.0$, indicating perfect negative correlation at -1.0 and perfect positive correlation at $+1.0$.

4.5.1 Maximum particle dispersion angle

To evaluate the variation of the particle dispersion angle, we examined the effects of ρ_p , d_p and d_n on the particle fall behavior. These three factors have a

significant influence on the dispersion angle. **Fig. 4-6** shows the effect of particle density on the particle dispersion angle, where three particle density values ($\rho_p = 3,600, 6,000, \text{ and } 7,800 \text{ kg/m}^3$) and two nozzle sizes ($d_n = 30 \text{ and } 40 \text{ mm}$) were used, with a particle diameter of 6 mm. We found that the dispersion angle variation in the experimental and simulation results showed a similar trend for both nozzle sizes. For $d_n = 30 \text{ mm}$, because of the strong interaction between the particles, which were relatively large compared to the small nozzle size, the lighter Al_2O_3 particles dispersed at a wider dispersion angle than the higher-density particles. A trend of increasing dispersion angle was observed for SS particles in both the experiments and the simulations due to strong particle–nozzle interactions between dense particles with larger size and relatively small nozzle size. However, this may indicate that the dependency of the dispersion angle on particle density becomes relatively small as the density increases. On the other hand, in the case of $d_n = 40 \text{ mm}$, because of the presence of intense mass flux in the particle jet, the particle–nozzle interaction mechanism had a more dominant effect than that of the particle–particle interaction in the experiments. The particle–nozzle interaction mechanism initiates a scattering effect on the falling particles, which causes the particles to detach from their initial falling path and to spread in widely spaced lateral directions. Because the particle–nozzle interaction effect in the experiments is larger than in the simulation, both the Al_2O_3 and SS particles in the experiment are laterally dispersed at larger dispersion angles than those predicted in the simulations for $d_n = 40 \text{ mm}$ (Fig. 4-6 (b)). This is because although the particle–nozzle interaction is more dominant than the particle–particle interaction, the particle–nozzle interaction is less intense in the simulations than in the experiment. Another reason for the deviation in the dispersion angle between the experimental and simulation results may be the one-way approach used

in the drag force calculation in the simulations. As a consequence, the effect of the drag force on the disperse particles is not properly reflected in the simulations for both $d_n = 30$ and $d_n = 40$ mm. A positive linear relationship estimated by the correlation coefficient was found between the experimental and simulated particle dispersion angles for $d_n = 30$ and 40 mm. The calculated correlation coefficient of the particle dispersion angle for $d_n = 30$ and 40 mm with 6 mm particles of Al_2O_3 , ZrO_2 , and SS was 0.99 and 0.93, respectively.

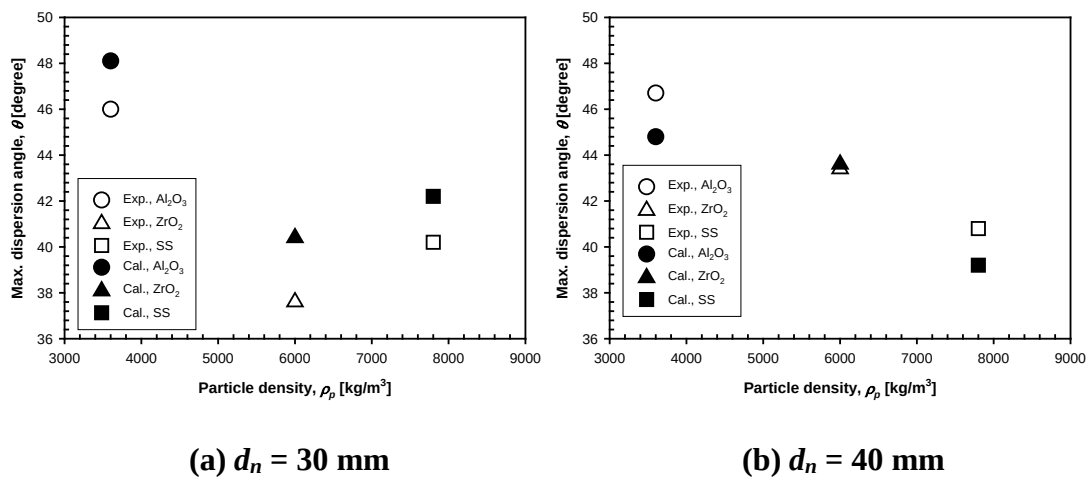


Fig. 4-6 Effect of particle density on particle dispersion angle θ for $d_n = 30$ and 40 mm with $d_p = 6$ mm.

Fig. 4-7 compares the profiles of the maximum particle dispersion angle for different particle diameters. Al_2O_3 and SS particles were used, with diameters of 2, 4, and 6 mm, and the nozzle sizes were 30 and 40 mm. A general trend of increasing dispersion angle with particle diameter is apparent with the exception of the 6 mm particles with the 40 mm nozzle for Al_2O_3 particles and with both nozzle sizes for SS particles. The increase in θ when d_p is larger may have been caused by the increasing fluid resistance for larger particles during particle–fluid interactions. We found good agreement between the experimental and calculated values of the dispersion angle for all the cases with both nozzle sizes. The calculated correlation coefficients

exhibit a strong positive relationship between the experimental and simulated particle dispersion angles. The correlation coefficient for Al_2O_3 particles was 0.99 in all the cases, whereas for SS particles the coefficients were 0.98 and 0.99 in the cases of $d_n = 30$ and 40 mm, respectively.

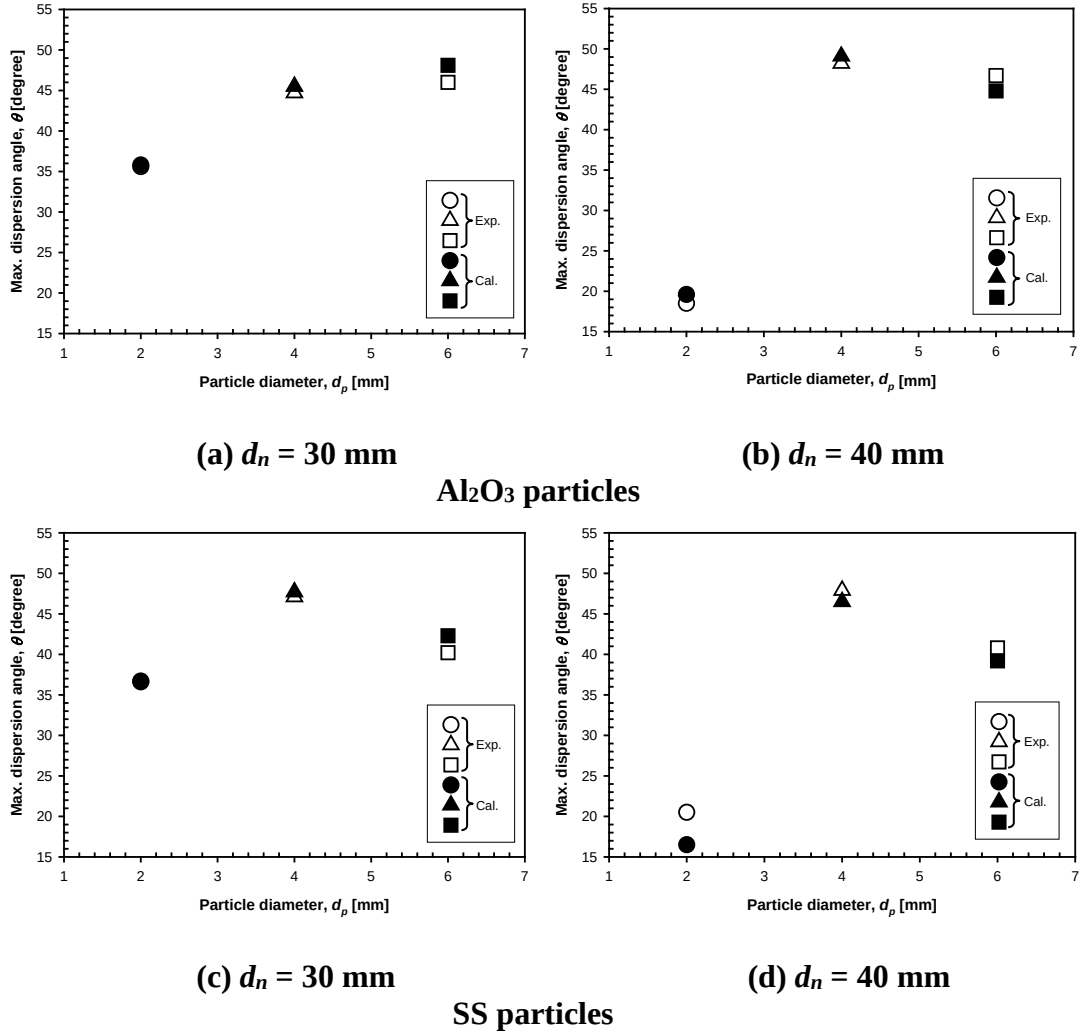


Fig. 4-7 Effect of particle diameter on particle dispersion angle θ for $d_n = 30$ and 40 mm in the cases of Al_2O_3 and SS particles.

Fig. 4-8 shows the influence of the nozzle size on the particle dispersion angle, indicating larger variations in the particle dispersion angle when the nozzle size is increased. The nozzle diameters were 20, 30, and 40 mm, and Al_2O_3 and SS particles of 4 mm diameter were used. The experimental and simulated results of the

dispersion angle variation had largely similar trend. Thus, the nozzle diameter can influence the particle sedimentation behavior. The correlation coefficients between the experimental and simulated results for the 4 mm particles of Al_2O_3 and SS were 0.99 and 0.95, respectively. A larger deviation between the experimental and simulated results was observed for smaller nozzle sizes. This is because in the narrow nozzle the particle–nozzle interaction is stronger, leading to an enhanced scattering effect on the particles; thus, more particles are dispersed at larger dispersion angles in the experiments than in the simulations. In principle, this type of particle–nozzle interaction is analogous to that of the particle–particle interaction although the effect of the particle–nozzle interactions on the sedimentation process is different than that of the particle–particle interactions. The reason is that in the particle–nozzle interactions the particles are in motion whereas the nozzle is steady, which causes higher deflection of the falling particles because of the glancing collision effect at the nozzle edge. In the case of Al_2O_3 particles, both in the experiments and simulations, increases in dispersion angle were observed for $d_n = 40$ mm. This is because the larger nozzle size produces a wide particle jet with a relatively larger mass flux for $d_p = 4$ mm. This particle jet causes strong particle–nozzle interactions initiating particle dispersion around the nozzle edge. Then, particle–fluid interactions eventually come into play with the initially dispersed particles enlarging the dispersion further. In our simulations, the material properties of the nozzle and the particles are similar. Thus, the parameters of the wall are almost the same as those of the particle and the properties of the nozzle wall are not well simulated. Better representation of the interactions between the particles and the wall should improve the dispersion angle discrepancy for small nozzle sizes.

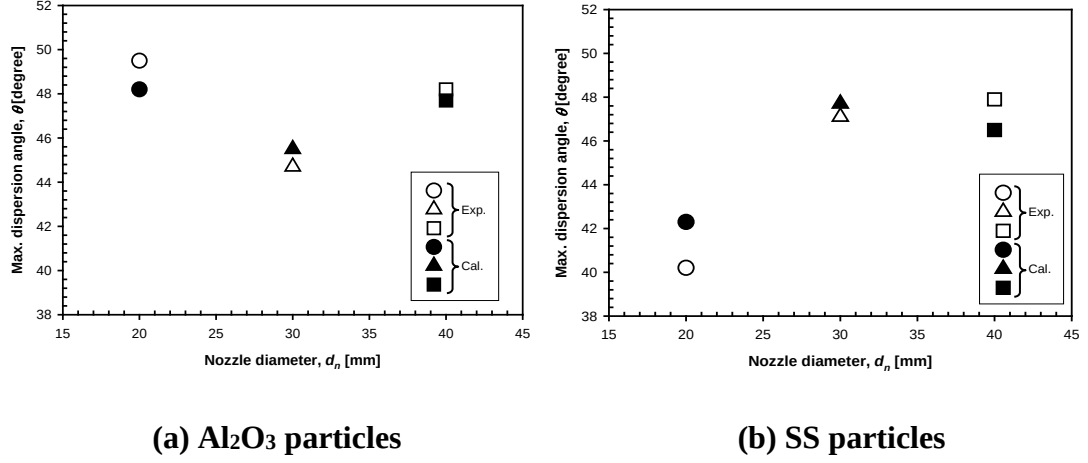
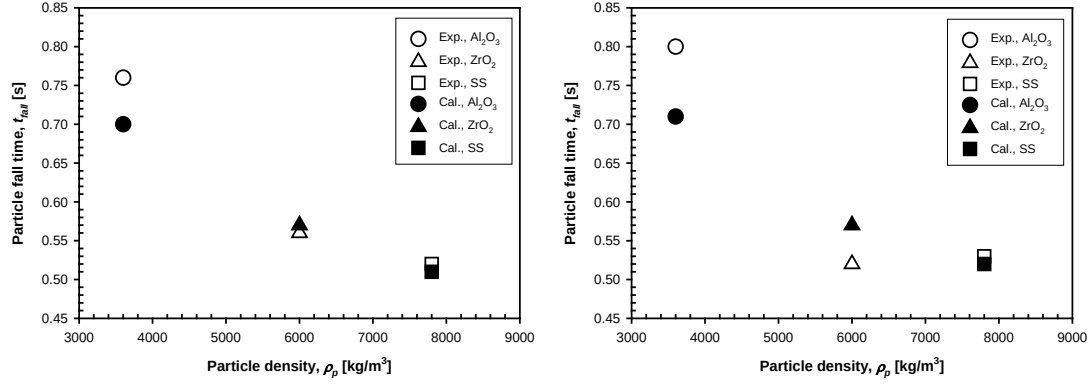


Fig. 4-8 Effect of nozzle diameter on particle dispersion angle θ for Al₂O₃ and SS particles with $d_p = 4$ mm.

4.5.2 Particle fall time

We define the particle fall time as the time taken by the front edge of the particle plume to reach the particle collector plate. We evaluated the particle fall time of the first particle batch for different densities ρ_p , particle diameters d_p , and nozzle sizes d_n (Figs. 4-9 to 4-11). The variation in the fall times of the different particles reflects the effect of the particle–fluid as well as the particle–nozzle interaction, which influences the particle sedimentation process that forms the particle bed.

Fig. 4-9 shows a decrease in particle fall time t_{fall} with increasing particle density ρ_p , which may be caused by gravity’s influence on the particles of different densities. In addition, strong particle–nozzle and particle–fluid interactions lead to longer particle fall times for the small and large particles, respectively. The dependency of particle fall time on particle density becomes smaller as the particle density increases. A reasonable agreement was observed between the experimental and calculated particle fall times of 6 mm particles of Al₂O₃, ZrO₂, and SS for $d_n = 30$ and 40 mm with a correlation coefficient of 0.99 and 0.96, respectively.



(a) $d_n = 30$ mm

(b) $d_n = 40$ mm

Fig. 4-9 Effect of particle density on particle fall time t_{fall} for $d_n = 30$ and 40 mm in the case of $d_p = 6$ mm.

Fig. 4-10 represents the effect of the particle size on the particle fall time. The dependency of the particle fall time on particle diameter becomes relatively small as the diameter increases. The particle fall time of the SS particles was shorter than that of the Al₂O₃ particles with $d_n = 30$ and 40 mm both in the experiments and simulations. A reasonable agreement is observed between the experimental and calculated values of t_{fall} with a larger deviation for the smaller particles for both cases of $d_n = 30$ and 40 mm. The particle fall time is larger for the smaller particles in both the experiments and simulations for $d_n = 30$ and 40 mm. This is because in both the experiments and simulations the small particles produce a particle jet with a dense mass flux, which increases the particle–fluid interaction causing longer t_{fall} . In addition, the front edge of the particle jet encounters fluid–particle drag because of the larger mass flux of the particle jet, which also prolongs t_{fall} . For both Al₂O₃ and SS particles with $d_p = 2$ mm, the larger deviation in t_{fall} between the experimental and simulated results may be due to the imprecise estimation of the drag force in the simulations based on the one-way approach. This may impose larger fluid drag on the particle stream, resulting in a longer t_{fall} than in the experiments. On the other

hand, for the Al_2O_3 particles of $d_p = 6$ mm with $d_n = 30$ and 40 mm, the deviation in t_{fall} may be due to inadequate treatment of the particle–nozzle interaction. During the falling process, the 6 mm particles are scattered further because of the strong particle–nozzle interaction effect in the experiments compared with the simulations, resulting in a longer t_{fall} in the experimental results. The correlation between the experimental and simulated results of particle fall time is relatively strong for $d_n = 30$ mm than for $d_n = 40$ mm. The calculated correlation coefficients in the cases of $d_n = 30$ and 40 mm were 0.99 and 0.77 for the Al_2O_3 particles, and 0.93 and 0.98 for the SS particles, respectively.

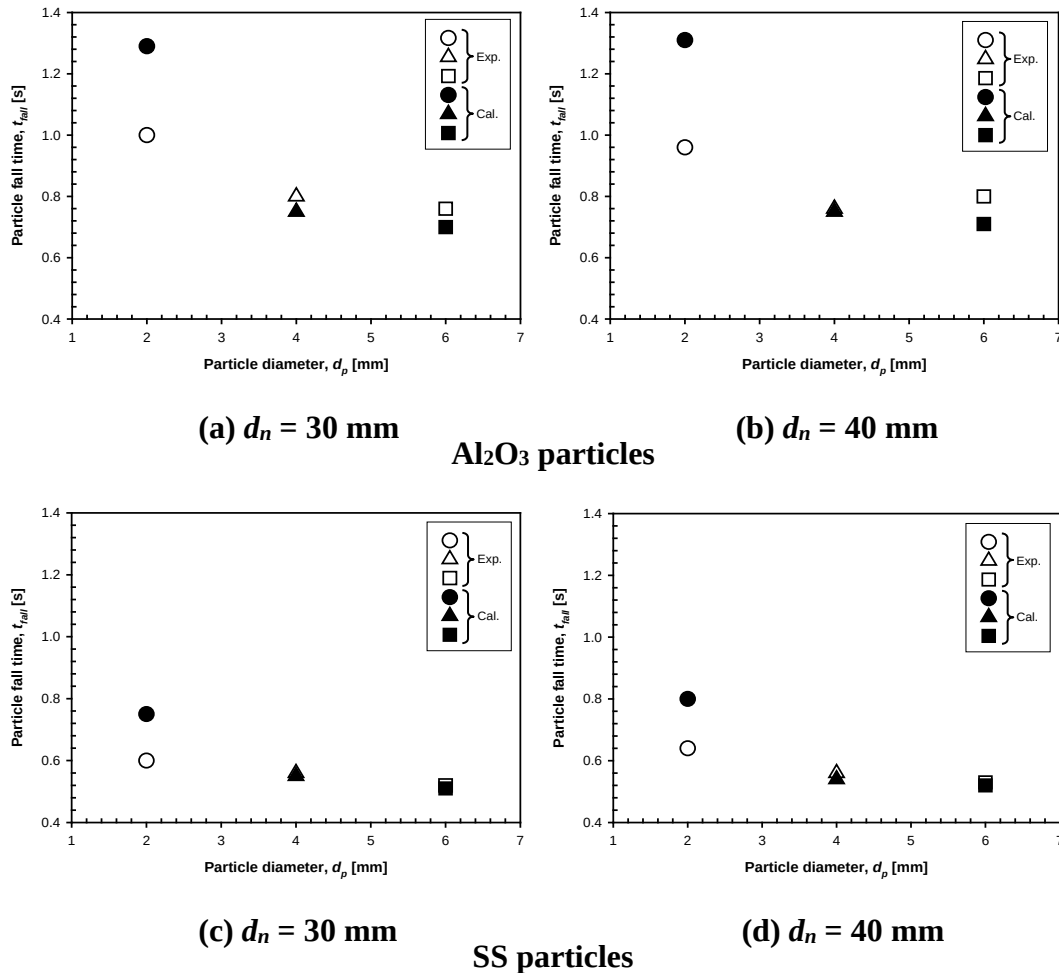


Fig. 4-10 Effect of particle diameter on particle fall time t_{fall} for $d_n = 30$ and 40 mm in the cases of Al_2O_3 and SS particles.

Fig. 4-11 shows the influence of the nozzle diameter on the particle fall time. Al_2O_3 and SS particles with a diameter of 4 mm were used and three nozzle sizes were compared: 20 mm, 30 mm, and 40 mm. In the experiments, a gradual trend of particle fall time variation was observed and relatively larger deviation was found between the experimental and simulation results for Al_2O_3 particles than that of SS ones. For the Al_2O_3 particles, when $d_n = 20$ mm, strong interactions cause longer t_{fall} in the experiment. This was not taken into account in the simulations (Fig. 4-11(a)). Because the particle–nozzle interactions have a stronger effect on the lighter particles, a notable deviation between the experiment and the calculation can be seen in the case of $d_n = 20$ mm for the Al_2O_3 particles. With the increase in nozzle size, the interaction effect reduces, and hence the difference between the simulation and the experiment becomes smaller. For the SS particles, the interactions between the particle and the nozzle have less effect on the particle sedimentation because of the larger particle density. Correspondingly, the dependence of t_{fall} on d_n is reproduced well in the simulations for the SS particles. The correlation between the experimental and simulated particle fall time was reasonable for both the Al_2O_3 and SS particles and their calculated correlation coefficients were 0.97.

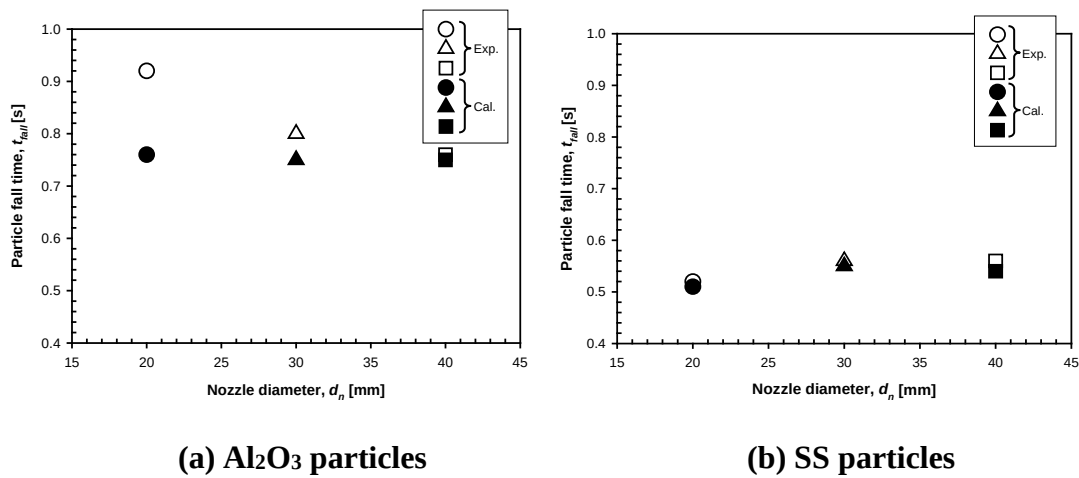


Fig. 4-11 Effect of nozzle diameter on particle fall time t_{fall} for Al_2O_3 and SS particles with $d_p = 4$ mm.

In the course of the present particle sedimentation process, the particle–nozzle interactions were dominant in comparison with the particle–particle and particle–fluid interactions. In the case of large nozzle size, the particle–fluid interactions became relatively large compared with the particle–particle ones. The nozzle size played a significant role on the particle–nozzle interactions for all of the particle sizes used in the present experiments, while both particle–particle and particle–fluid interactions were strongly affected by the particle size.

4.5.3 Maximum bed height

Evaluating the bed height H_b and the quantitative bed shape is important for reactor safety to estimate the coolability of the debris bed when analyzing whether a core in such a condition of geometric disarray can regain criticality. **Fig. 4-12** shows the variation of particle bed height with respect to particle density for the experimental and simulated results. Three different particle densities were used (of Al_2O_3 , ZrO_2 , and SS) and two nozzle diameters, with particle diameter of 6 mm. The correlation coefficient between the experimental and simulated bed height results was 0.73 and 0.99 for $d_n = 30$ and 40 mm, respectively. A general trend of gradual decrease in H_b with density is observed in both the experiments and simulations with an exception of the SS result for $d_n = 30$ mm. The dependency of bed height on particle density becomes relatively small as the density increases. The reason for this can be the effect of particle dispersion angle and particle fall time on H_b . This is because a smaller particle dispersion angle due to increased particle density increases the gravity impact of the particle jet, which eventually pushes the bed-top downward. Similarly, the decrease in particle fall time for higher-density particles reflects the lower particle–fluid drag effect that increases the gravity impact on the particle jet.

This results in a lower H_b that is larger for higher-density particles than for lower-density ones.

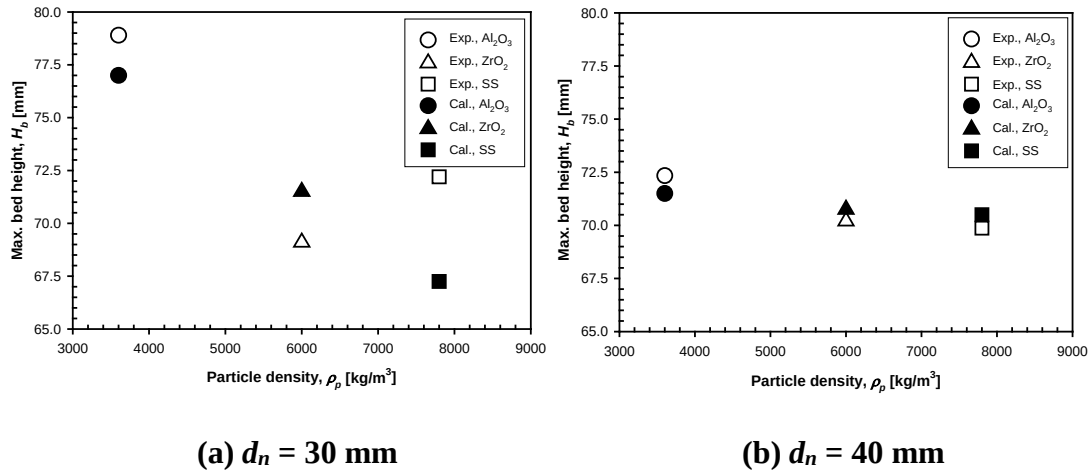


Fig. 4-12 Effect of particle density on bed height H_b for $d_n = 30$ and 40 mm in the case of $d_p = 6$ mm.

Fig. 4-13 presents the effect of particle diameter on bed height H_b for Al_2O_3 and SS particles. We used particles with diameters of 2, 4, and 6 mm and nozzle diameters of 30 mm and 40 mm. A similar trend was found between the experimental and simulated bed height data, with a correlation coefficient of 0.89 and 0.99 in the case of Al_2O_3 particles, and 0.98 and 0.99 in the case of SS particles for $d_n = 30$ and 40 mm, respectively. In the case of Al_2O_3 particles, both the experiments and simulations showed an increasing trend of H_b with increasing d_p for $d_n = 30$ mm with an exception in the case of $d_n = 40$ mm with $d_p = 6$ mm. The increment of H_b is mainly because of the decreasing particle jet impact on the top of the bed, caused by the increase in particle dispersion angle with larger d_p . In the experiments and simulations, the dispersion angle was smaller for $d_p = 2$ mm and larger for $d_p = 6$ mm. For the smaller particle diameter, the smaller dispersion angle causes a larger particle flux in the particle jet. This particle jet with larger mass flux imposes a larger impact on the top of the bed because of gravity. For $d_p = 6$ mm, the

impact of the particle jet decreases with increasing dispersion angle. The eventual decrease of the particle jet impact causes an increase in H_b in both the experiments and simulations in the case of $d_n = 30$ mm. The same effect can explain the decrease of H_b from $d_p = 4$ to 6 mm in the case of $d_n = 40$ mm for Al_2O_3 particles, and in the cases of $d_n = 30$ and 40 mm for SS particles, where the particle jet impact rises as the dispersion angle decreases for $d_p = 6$ mm. The difference in bed heights between the experimental and simulated data may be caused by the rough estimation of the fluid drag. This assumption may have resulted in an inaccurate calculation of the effect of fluid drag on the particle dynamics.

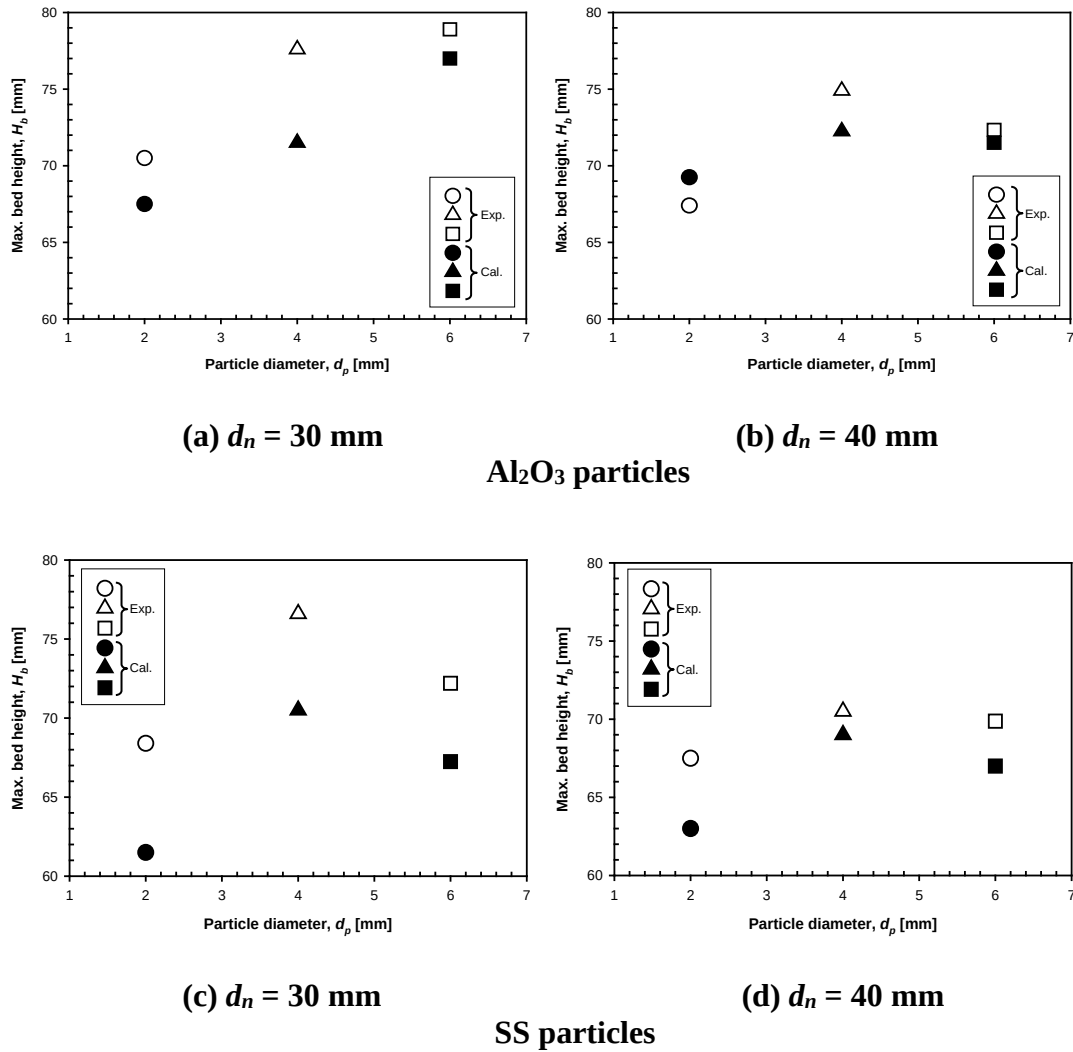


Fig. 4-13 Effect of particle diameter on bed height H_b for $d_n = 30$ and 40 mm in the cases of Al_2O_3 and SS particles.

If the fluid drag is underestimated in the simulations, the vertical downward motion of the particles would be larger causing H_b to be smaller than in the experiments, which is apparent in the case of $d_n = 30$ mm for Al_2O_3 particles (Fig. 13 (a)) and in both cases of $d_n = 30$ and 40 mm for SS particles (Fig. 4-13 (c) and (d)).

Fig. 4-14 shows the bed height variation with nozzle diameter for Al_2O_3 and SS particles with $d_p = 4$ mm. The effect of nozzle diameter on H_b is more apparent in the case of the larger nozzle size for the SS particles than for the Al_2O_3 particles. This is because of the larger effect of the particle jet impact on the top of the bed resulting from the larger gravity effect of the denser SS particles with a nozzle size of 40 mm. There is better agreement between the experiments and simulations for the SS particles than for the Al_2O_3 particles. The larger deviation between the experiments and simulations for the Al_2O_3 and SS particles may be due to the smaller effect of fluid drag on the lighter particles in the one-way simulations, which would overestimate the impact of the particle jet on the top of the bed. For the Al_2O_3 particles, a reasonably strong linear relationship was found between the experimental and simulated bed heights and the correlation coefficient was 0.94, while it was 0.72 for the SS particles.

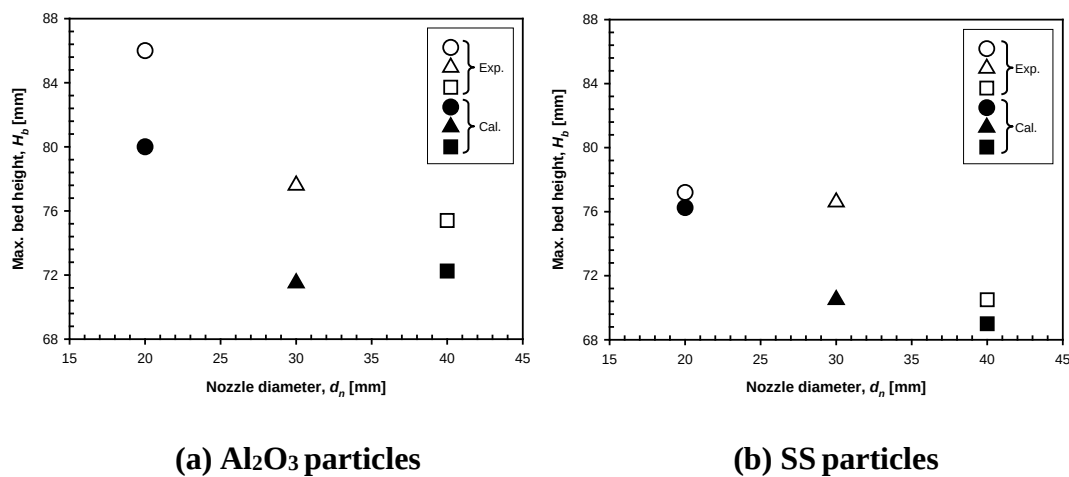
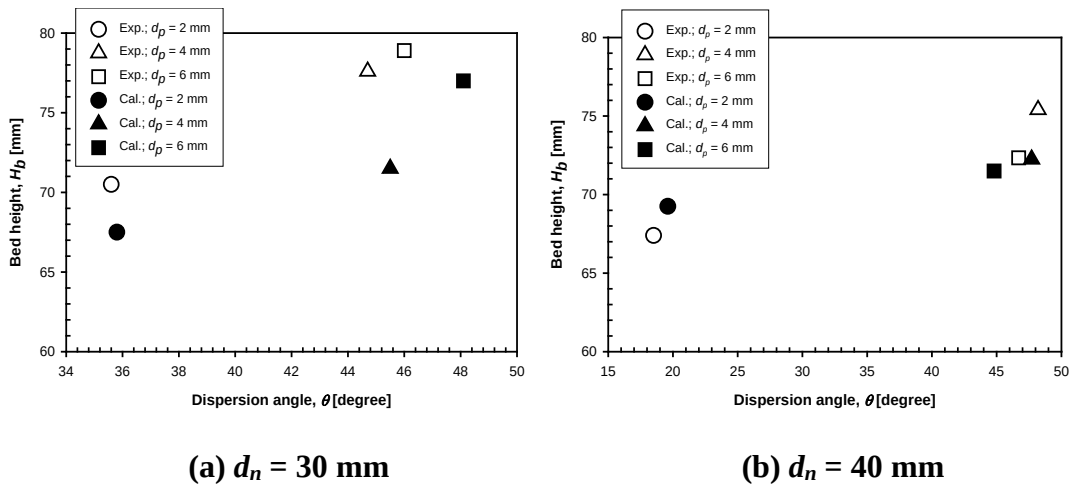


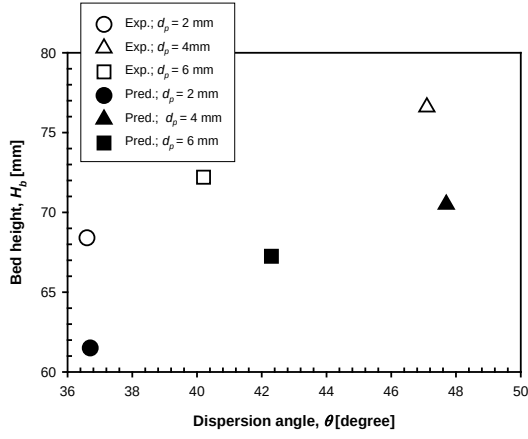
Fig. 4-14 Effect of nozzle diameter on bed height H_b for Al_2O_3 and SS particles with $d_p = 4$ mm.

The relationships between θ and H_b and between t_{fall} and H_b are analyzed individually for the same material by considering d_p as a parameter in the cases of Al_2O_3 and SS particles. This is because we did not observe remarkable dependency on particle density in a general trend as well as the effect of H_n was not studied in the simulations. In addition, we did not consider d_n as the parameter, because only the case of $d_n = 40$ mm indicated a major influence on H_b regardless the degree of dispersion in these relationships. This is because in the case of $d_n = 40$ mm the gravity effect of the particle jet is much dominant on the resultant bed height than that of particle dispersion.

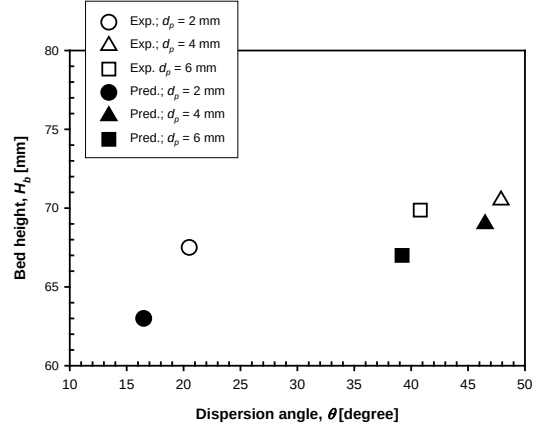
Fig. 4-15 shows the variation of H_b with θ . Here H_b increased in both the experiments and simulations as θ increased for both $d_n = 30$ and 40 mm in the cases of Al_2O_3 and SS particles. **Fig. 4-16** presents the variation of H_b with t_{fall} . In the case of Al_2O_3 particles with $d_n = 30$ mm, H_b decreases with increasing t_{fall} . For $d_n = 40$ mm the experimental H_b decreases with increasing t_{fall} ; however, in the simulation, the decreasing trend of H_b is broken in the case of the particles with $d_p = 6$ mm. In the case of SS particles the decreasing trend of H_b is broken for $d_p = 6$ mm both with $d_n = 30$ and 40 mm in both the experiments and simulations.



Al₂O₃ particles



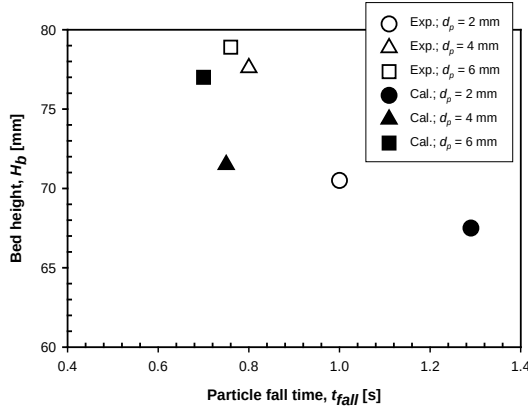
(c) $d_n = 30$ mm



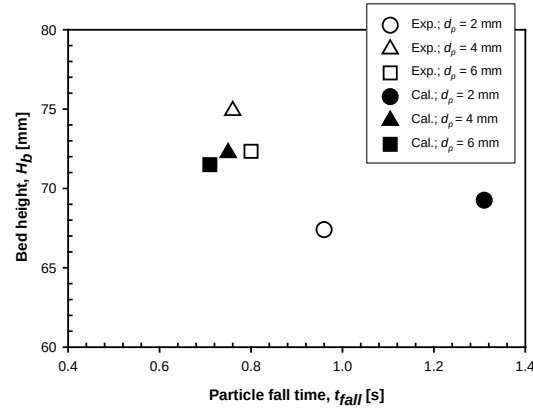
(d) $d_n = 40$ mm

SS particles

Fig. 4-15 Bed height variation with dispersion angle θ for $d_n = 30$ and 40 mm in the cases of Al₂O₃ and SS particles with $d_p = 2$, 4 , and 6 mm.

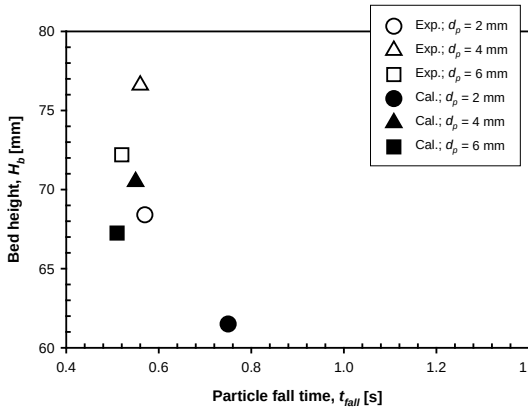


(a) $d_n = 30$ mm

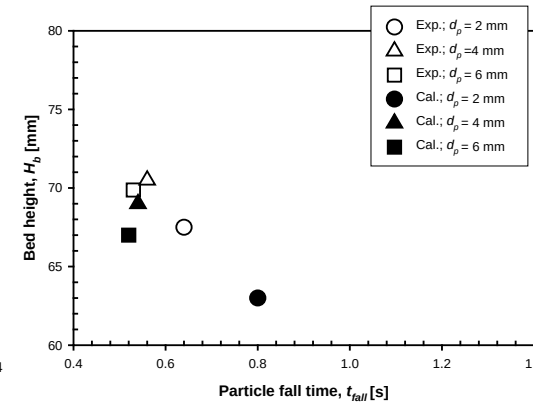


(b) $d_n = 40$ mm

Al₂O₃ particles



(c) $d_n = 30$ mm



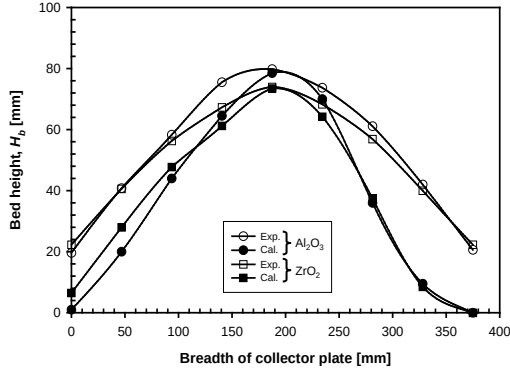
(d) $d_n = 40$ mm

SS particles

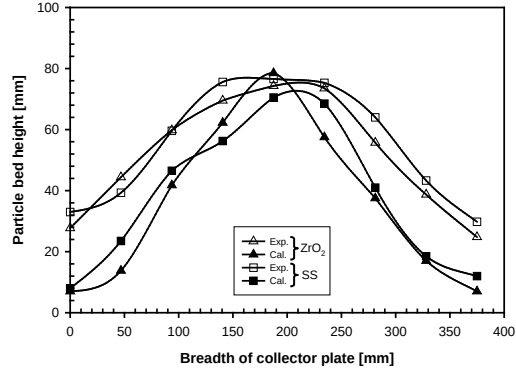
Fig. 4-16 Bed height variation with particle fall time t_{fall} for $d_n = 30$ and 40 mm in the cases of Al_2O_3 and SS particles with $d_p = 2, 4$, and 6 mm.

4.5.4 Quantitative bed shape

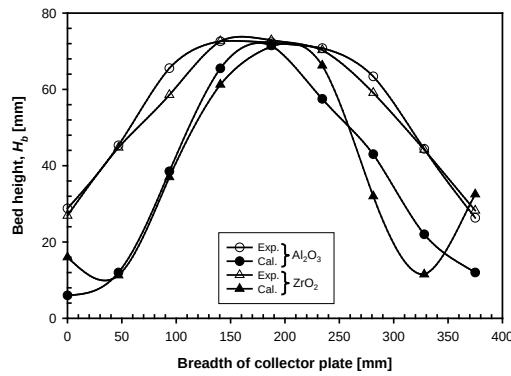
Fig. 4-17 shows the characteristic features of the bed shape formed by the Al_2O_3 , ZrO_2 , and SS particles. The bed shape is defined as the contour of the bed height along the particle collector plate. The simulated bed shapes are similar to those of the experimental ones. The trend of the bed shape in the experiments and simulations indicates an almost similar lateral sedimentation pattern for all particle sizes. Comparing the experimental and simulated bed heights, the difference is smaller at the top of the bed and increases at the lateral points away from the top of the bed. This difference may be due to insufficient modeling of the impact of the particle jet on the bed-top in the simulations, forming a minor depression on the bed-top. As a result, the particles do not dissipate effectively in the lateral directions. This small particle sedimentation in the lateral direction leads to a simulated bed height that is smaller than that found in the experiments. In our comparison, the bed-top was flatter with the larger nozzles than with the smaller one. This is more evident in the experimental beds than in the simulated beds. In the experiments, the bed height rises at the edges when the particles accumulate laterally as well as fall vertically, causing interactions between the dispersed particles and the pool wall for the particles with $d_p = 4$ mm and 6 mm. However, in the simulations, this elevated bed edge is observed only at the adjacent points of the pool wall when dispersed particles fall down, causing interactions with the pool wall as in the case of $d_p = 6$ mm (Fig. 4-17(c)).



(a) $d_p = 2 \text{ mm}$; $d_n = 20 \text{ mm}$



(b) $d_p = 4 \text{ mm}$; $d_n = 30 \text{ mm}$



(c) $d_p = 6 \text{ mm}$; $d_n = 40 \text{ mm}$

Fig. 4-17 Comparison of quantitative bed shapes of experiments and simulations for various particle diameters and densities, and nozzle diameters.

Although the particle–particle and particle–fluid interactions cause 3D movement of particles locally, it is expected that falling and settling particles indicate 2D bulk behaviors in the cylindrical pool under the present experimental conditions. In fact, the experimental results showed that the particle beds were formed in roughly axisymmetric shapes as can be seen in Fig. 17. One of the aims of the present simulations is to predict the observed shapes of particle beds in a vertical cross section along the cylindrical axis using the proposed method. Although the present 2D representation is a rough simplification for the simulations of the bulk particle behaviors in the cylindrical pool, there could be some similarity between 2D and 3D systems in characteristics of the bulk behaviors of falling and settling

particles. This is because it is expected that the bulk behaviors in the two systems will present similar dependency on key factors such as particle size and density, the nozzle size, and so on. Therefore, it is useful to know qualitative applicability of the present one-way method to the simulation of bulk particle behaviors even under the 2D restriction for extension of the present method to 3D systems, which is considered as our future research work.

4.6 Extrapolation to sodium-fuel system

The application scope of the DEM based model and the proposed empirical correlation has been investigated in the sodium-fuel system. The comparative assessment of the extrapolated trend of H_b respective to the predicted and estimated results can be useful as the baseline for the further improvement of those models. The main purpose of this study is to check the congruence between the predicted and estimated trend of H_b in the extrapolated range with sodium-fuel system using the DEM based code and the developed empirical correlation.

4.6.1 Extrapolation with DEM model

To verify the DEM based code of particle sedimentation model, we compared the simulation results with the experiments in the case of spherical particles with $H_n = 720$ mm. The model predictions are verified in terms of the nozzle diameter, particle density and particle diameter based on the experimental observations as discussed in Section 4.5. Simulation results exhibit a reasonable agreement with the experimental observations in each case. This suggests that the present model is valid and reasonable. Therefore, extrapolation to sodium-fuel system can be made to check the trend of the model predictions with some degree of confidence. **Fig. 4-18** presents the extrapolation of model predictions for estimate H_b in the sodium-fuel

system with $d_n = 30$ and 40 mm. Currently, we considered the fuel density of 10,000 kg/m³ at 1773 K as well as the coolant density and viscosity of 830 kg/m³ and 2.4×10^{-4} Pa·s, respectively at 773 K to verify the validity of extrapolation in the sodium-fuel system. It is seen that in the extrapolated zone, the decreasing trend of H_b became more obvious in the case of $d_n = 40$ mm than that of $d_n = 30$ mm with an exception of $d_p = 6$ mm. We found H_b in an increasing trend with the particle diameter both in the predicted and extrapolated range with an exception at 6000 kg/m³ and 7800 kg/m³ for $d_n = 30$ and 3600 kg/m³ and 7800 kg/m³ for $d_n = 40$ mm. In general, an indication on reproducing a similar trend of the experimentally validated prediction result is achieved in the case of extrapolation.

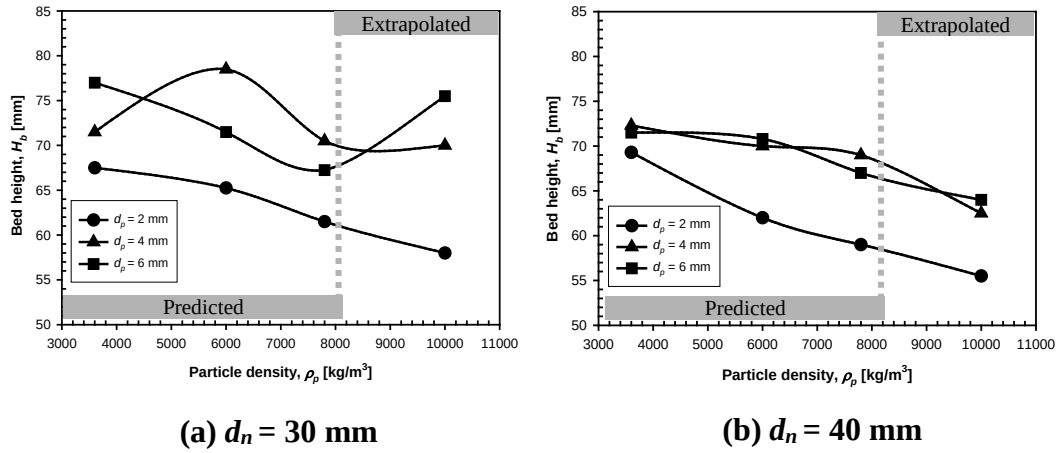


Fig. 4-18 Extrapolation of the simulated H_b trend in the sodium-fuel system for spherical particles with DEM model ($H_n = 720$ mm).

4.6.2 Extrapolation with empirical correlation

We evaluated the estimated H_b in the case of spherical simulant particles with water as coolant using the proposed empirical correlation, Eq. (3-7). We believe that extrapolation of the estimated results in water-particle system to the sodium-fuel system will authenticate the application scope of this empirical correlation in the case of reactor conditions. Prior to the extrapolation, we verified the estimated

results in the water-particle system with the empirical correlation based on the particle sedimentation experiments. This verification of the estimated results in terms of nozzle diameter, particle density, particle diameter and nozzle height are discussed in Section 3.3. The predictions in water-particle system reasonably agreed with the experimental observations. This indicates the possibility of extrapolation in the sodium-fuel system with the current empirical correlation. The extrapolated results in sodium-fuel system are shown in **Fig. 4-19**. In the estimated zone, the density dependency of H_b became small with a gradual upward trend of H_b when density was increased. This upward trend of H_b was further developed when the estimated results are extrapolated to the sodium-fuel system. This indicates the occurrence of H_b elevation in the case of larger density fuel debris sedimentation into the sodium coolant. This might be due to the reason of particle-particle frictional drag which resists the lateral sedimentation of the larger density fuel particles. Regarding particle size effect in both the estimated and extrapolated zone, H_b was observed increasing with the particle diameter in the case of $d_n = 40$ mm with an exception at larger density range for $d_n = 30$ mm. However, the estimated trend with particle density effect indicates a deviation with the extrapolated trend.

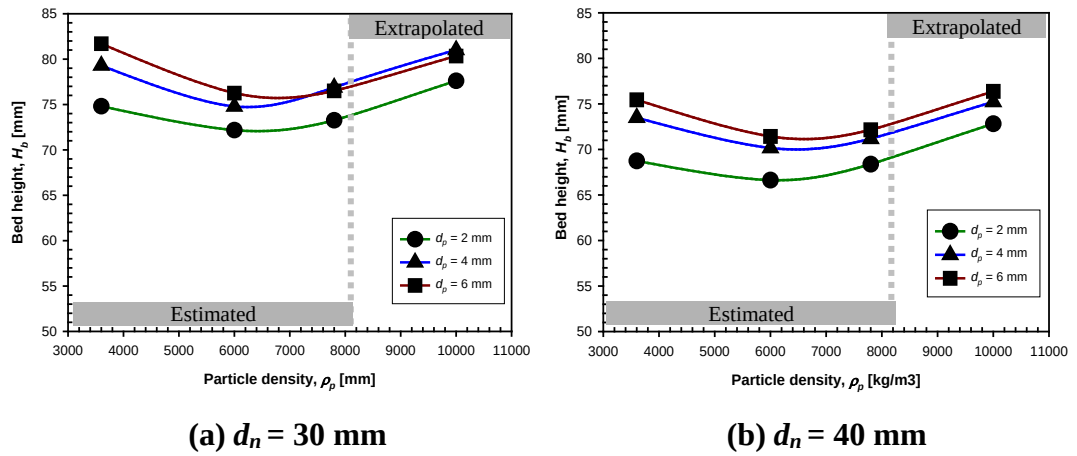


Fig. 4-19 Extrapolation of the estimated H_b trend in the sodium-fuel system for spherical particles with empirical correlation ($H_n = 720$ mm).

4.6.3 Comparative analysis of simulated and estimated H_b

In the comparative analysis of H_b between the simulated results of the DEM model and predictions of the empirical correlation, a similar decreasing tendency was observed within the density range 3600 to 6000 kg/m³ in the cases of both $d_n = 30$ and 40 mm with an exception of $d_p = 4$ mm for $d_n = 30$ mm, as shown in Figs. 4-18 and 4-19. In the density range 6000 to 7800 kg/m³, a small dependency of H_b on the density was observed indicating an upward trend for the empirical correlation and a downward trend in the simulations. In the extrapolated zone, a general descending trend of H_b was observed in the simulations, whereas this trend was found in an increasing fashion in the case of predictions with empirical correlations. The degree of upward development of H_b in the extrapolated zone with empirical correlation seems to be overestimated, which does not consistent with small density dependency of the estimated H_b . Conventionally, a descending trend of H_b should appear in the extrapolated zone which is, however, did not observe; although the fuel density is relatively large and the coolant density and viscosity in the case of sodium is smaller than that of the water.

4.7 Summary and concluding remarks

The model predictions were evaluated and compared to the experimental observations in terms of three key quantitative parameters: the maximum particle dispersion angle θ , the particle fall time t_{fall} , and the bed height H_b to quantify the sedimentation process. A parametric study was performed with these key quantitative parameters to identify the role of the crucial factors on model predictions. The model predictions reasonably demonstrate the important role of the particle dispersion angle in determining the height and shape of the bed, which in

turn can affect the coolability of the debris bed. In general, larger fluctuations were found in dispersion angle in the case of $d_n = 40$ mm indicating a good agreement between experiments and predictions for all crucial parameters. This simply indicates that model predictions can reasonably interpret the experimental dispersion angle within an acceptable degree of accuracy. In addition, the present simulation model satisfactorily predicts the particle fall time which mainly varies based on the particle–fluid interactions. Further, the predicted bed height indicates the similar trend of variation with the experiments for all crucial factors, although some differences are still observed. In general, the particle-nozzle interactions play a vital role on causing deviations between experimental and simulation results. In the present study the DEM based simulation code demonstrates the fundamental applicability of the proposed simulation model to some basic characteristics of sedimentation behaviors with spherical particles.

The extrapolated results in the sodium-fuel system have been verified with the proposed empirical correlation and the DEM based model. An upward trend of the estimated H_b was recognized in the extrapolated zone with the empirical correlation, whereas a descending trend was observed with the extrapolated simulation results of DEM model. The prediction consistency of both the empirical correlation and the DEM model needs to be optimized in the larger density range to establish a sound congruence between the extrapolated predictions and simulation results.

Chapter 5

CONCLUSIONS

The particle bed characteristics during particle sedimentation process have been investigated from the viewpoint of reactor safety concern in the post-accident material relocation (PAMR) phase of SFRs. The nozzle diameter d_n , particle density ρ_p , particle diameter d_p , and nozzle height H_n have been identified as the governing crucial factors. We investigated the effect of these four crucial factors where their role has been well demonstrated on the particle bed shape in the course of sedimentation process. The diversity in the bed shape transformation from convex to concave has been recognized in accordance with the influence of crucial factors. In this study, the particle bed characteristics in terms of the key quantitative parameters, mound height H_m , mound dimple area A_{dim} , mound dimple volume V_{dim} , and repose angle θ_r were evaluated by employing three types of spherical particles with different size. The general tendency of forming relatively larger mound elevation was observed with smaller nozzle size and lower particle density, as well as larger particle size and small nozzle height, respectively. The difference in the bed shapes between the spherical and non-spherical particles has been evaluated, where particle shape pronounced a key role on forming the mound shape. To replicate the debris sedimentation behavior under reactor accident conditions, our future work will include a wide range of particle sphericity to verify the particle-particle frictional resistance as well as the particle-fluid interacting drag on changing the bed shape.

An empirical correlation was developed based on the data obtained in the experimental observations to predict the bed height H_b reasonably. The proposed empirical correlation can estimate the experimental values of H_b within a fair degree

of accuracy (with RMS error of 4.5 mm) under current experimental conditions. These predictions can rationally reproduce the remarkable effects of the aforesaid four crucial factors indicating almost a similar trend of H_b variation. The reliability of the proposed empirical correlation was authenticated by initiating detailed analysis of the effect of current experimental parameters. However, the prediction accuracy of the proposed empirical correlation needs to be improved further. To improve the application scope of the proposed empirical correlation to reactor conditions, further investigations are needed by extending the range of present experimental parameters (such as d_n , d_p , ρ_p , H_n and v_i) including diversity in non-spherical particles and thermal conditions. Nevertheless, the proposed empirical correlation can reasonably demonstrate the general trend of H_b variation in accordance with some crucial factors. This could be useful to study the particle bed formation characteristic with a view to identify critical parameters, which may reasonably influence particle sedimentation behaviour.

A comparative study involving a series of experiments and simulation runs was performed to evaluate the general trend of model predictions during sedimentation of solid particles used as simulant debris particles. We evaluated the effect of three crucial factors: ρ_p , d_p , and d_n on the sedimentation process. We compared the maximum particle dispersion angle, particle fall time, bed heights and quantitative bed shapes formed by the fallen particles. In general, we found good agreement between the experiments and the simulations, with some noticeable discrepancies. We believe that the difference between the experimental and simulated results came from the simplified treatment of the particle–nozzle interaction in the simulations. Our simulation results demonstrate the role of ρ_p , d_p , and d_n in the particle sedimentation behavior. Consequently, obvious effects of ρ_p , d_p ,

and d_n were observed in the patterns of the particle dispersion angle, particle fall time, and particle bed height. A larger variation in the particle fall pattern expressed by the particle dispersion angle was observed with smaller particle density, whereas a smaller variation in the fall pattern was observed for larger particle diameter. In addition, the variation in the particle bed height became relatively small as the density increased, whereas notable variation in the bed height was observed when the particle diameter increased. A descending trend of H_b was observed with increased nozzle diameter both in the experiments and simulations. This trend of H_b variation was reproduced well in the extrapolated range of reactor situation. The simulation results indicate the possibility of using DEM based simulation techniques for investigating the particle sedimentation behavior. However, to improve the prediction accuracy of the present code, appropriate treatment of particle–fluid and particle–wall interaction behavior may be necessary. To reduce the deviations observed in our simulation results, our future work will incorporate the two-way approach of drag force calculations to take into account the fluid flow effect on particle dynamics. Moreover, we plan to perform 3D simulations for comprehensive evaluation of the 2D results to investigate the particle sedimentation process in a more realistic manner.

The prediction capacity of the DEM based model and the proposed empirical correlation has been investigated in the extrapolated zone of sodium-fuel system. The inconsistency between the simulated predictions and estimated evaluations of H_b trend in the extrapolated range suggests further improvement to establish a sound congruence.

The present experiments were performed with a view to clarify the particle bed formation mechanism so as to identify the governing crucial factors on the

sedimentation process. This fundamental experimental database of particle sedimentation phenomena has a worth to be utilized as the baseline to verify and improve the relevant models and methods of fast reactor safety analysis codes. The possibility of forming a flatten shaped bed, as the current experiments revealed depending on the role of crucial factors, can be a motivation point of analyzing the debris bed shape in a coolable configuration, which needs to be investigated further. We believe that based on the reasonable extrapolation of the present experimental results, debris bed shape can be optimized to estimate the limit conditions of coolability, while forming onto the debris tray. Thus, the present experiments have a prospective application scope to verify the IVR safety strategy, as a final safety goal of JSFR against ATWS type CDA, concerning the coolable debris bed configuration for the safe stabilization of molten core material.

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Finally, I dedicate this thesis to my beloved parents.

Nomenclature

A_{dim}	dimple area	[m ²]
d_n	nozzle diameter	[m]
d_p	particle diameter	[m]
d_b	bed diameter	[m]
D_c	cylinder diameter	[m]
h_b	average bed height	[m]
H_b	bed height	[m]
H_m	mound height	[m]
H_n	nozzle height	[m]
J_f	jet factor	[-]
j_m	particle mass flux	kg/m-s
N	particle number	[-]
t_{fall}	particle fall time	[s]
Δt	time step size	[s]
V_A	Volume of bed mound	[m ³]
V_B	Volume of bed edge	[m ³]
V_{dim}	dimple volume	[m ³]
V_b	total particle bed volume	[m ³]
V_p	bulk particle volume	[m ³]
v	particle velocity relative to fluid	[m/s]
v_i	initial velocity	[m/s]
v_p	particle velocity	[m/s]
v_t	terminal velocity	[m/s]

Greek letters

α_{tn}	stiffness correlation constant	[-]
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α_{cn}	damping correlation constant	[-]
ν	poisson's ratio	[-]
μ	friction coefficient	[-]
μ_f	fluid viscosity	[Pa·s]
ρ_f	fluid density	[kg/m ³]
ρ_p	particle density	[kg/m ³]
θ	maximum dispersion angle	[degree]
θ_r	repose angle	[degree]
ε	porosity	[-]
φ	sphericity	[-]

Subscripts

b	bed
c	cylinder
dim	dimple
i	initial
m	mound
n	nozzle
p	particle
r	repose
t	terminal

Abbreviations

Cal.:	Calculation
Exp.:	Experiment
Min	Minimum
Max	Maximum
Pred.:	Predicted

Legend



Convex shaped bed



Concave shaped bed

Acronyms

ANL	Argonne National Laboratory
ATWS	Anticipated Transient Without Scram
BR	Breeder Reactor
CDA	Core Disruptive Accident
CGRT	Control Rod Guide Tube
CRBR	Clinch River Breeder Reactor
DEM	Discrete Element Method
DOE	Department of Energy
EIA	Energy Information Administration
EBR	Experimental Breeder Reactor
FBR	Fast Breeder Reactor
FCI	Fuel-Coolant Interaction
FFTF	Fast Flux Test Facility
GIF	Generation IV International Forum
GW	Gigawatt
GFR	Gas-Cooled Fast Reactor
IAEA	International Atomic Energy Agency
INES	International Nuclear and Radiological Event Scale
ITER	International Thermonuclear Experimental Reactor
L	Liter
LFR	Lead-Cooled Fast Reactor

LMFBR	Liquid Metal-Cooled Fast Breeder Reactor
LMR	Liquid-Metal-Cooled Reactor
LWR	Light Water Reactor
MW	Megawatt
MWe	Megawatt Electrical
MWt	Megawatt Thermal
MLT	Mass Length Time
MOX	Mixed Oxide
MSR	Molten-Salt Reactor
NEA	Nuclear Energy Agency
OECD	Organization Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PFR	Prototype Fast Reactor
PAHR	Post-accident Heat Removal
PAMR	Post-Accident Material Relocation
PIV	Particle Image Velocimetry
RMS	Root-Mean-Square
SCWR	Supercritical-Water Cooled Reactor
SFR	Sodium-Cooled Fast Reactor
SS	Stainless steel
UK	United Kingdom
USA	United States of America
USSR	Union of Soviet Socialist Republics
VHTR	Very-High-Temperature Reactor
WNA	World Nuclear Association

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