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Comprehensive Analysis of Bidisperse Fluidized-Bed Kinetics Under Coupled Heat Transport

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ABSTRACT

Fluidized beds operating with bidisperse particle mixtures are integral to numerous industrial processes, including coal gasification, biomass combustion, and catalytic cracking. The complex interplay between particle kinetics and thermal transport in these systems presents significant challenges for process optimization and scale-up. This paper provides a comprehensive investigation into the kinetic behavior of bidisperse fluidized beds under the influence of coupled heat transport mechanisms. By integrating the kinetic theory of granular flow with Eulerian-Eulerian multiphase modeling, this study delineates the precise hydrodynamic and thermal interactions between particles of varying sizes and densities. The research systematically examines segregation and mixing phenomena, emphasizing how localized temperature gradients alter gas viscosity and, consequently, fluidization hydrodynamics. A rigorous methodological framework is established to quantify interphase heat transfer coefficients and particle collision frequencies across a spectrum of operating conditions. The findings reveal that bidisperse mixtures exhibit distinct thermal distribution profiles compared to monodisperse systems, primarily due to the differential drag forces and percolation velocities inherent in disparate particle populations. Furthermore, the introduction of coupled heat transport equations demonstrates that thermal expansion of the fluidizing medium significantly modifies the minimum fluidization velocity of the finer particle fraction, thereby accelerating transient segregation states. These insights offer a robust theoretical and empirical foundation for designing highly efficient multiphase reactors where precise temperature control and uniform mixing are paramount.

KEYWORDS

Bidisperse Fluidization, Heat Transport, Particle Kinetics, Multiphase Flow

1. Introduction

Fluidized beds are universally recognized for their exceptional heat and mass transfer capabilities, which stem from the intense mixing of solid particles suspended in a fluidizing medium. While monodisperse systems have been extensively studied and mathematically formalized over the past several decades, industrial applications rarely operate with perfectly uniform particles. The reality of chemical and biochemical engineering processes necessitates the use of continuous particle size distributions or, in many targeted applications, bidisperse mixtures consisting of two distinct particle sizes or densities. The kinetic behavior of such bidisperse systems is inherently more complex than their monodisperse counterparts due to the competing mechanisms of mixing and segregation. When coupled with heat transport, this complexity is magnified exponentially. Temperature variations within the reactor alter the physical properties of the fluidizing gas, which cascades into changes in drag forces, particle collision dynamics, and overall bed hydrodynamics. Chen and colleagues examine flow behaviors in a fluidized bed reactor with binary mixture of Geldart-A and B particles [1]. The critical importance of understanding bidisperse fluidized-bed kinetics under coupled heat transport cannot be overstated. In processes such as biomass gasification or the combustion of municipal solid waste, the feedstock typically comprises a wide range of particle sizes. The smaller, lighter particles may combust rapidly and release substantial thermal energy, while the larger, denser particles act as thermal reservoirs and structural stabilizers within the bed. If the heat transport between these distinct particle phases and the fluidizing gas is not thoroughly understood, the reactor may suffer from localized hot spots, agglomeration, or defluidization. Consequently, establishing a robust theoretical and empirical framework to predict the behavior of these systems is a primary objective for contemporary chemical engineering research. Despite the recognized importance of this field, there remains a notable gap in the literature regarding the exact mechanistic coupling between granular kinetics and thermal dynamics in bidisperse systems. Early investigations primarily treated heat transfer and hydrodynamics as decoupled phenomena, assuming isothermal conditions to simplify the mathematically demanding Navier-Stokes equations applied to multiphase flows. However, this decoupling fundamentally misrepresents the physical reality of high-temperature industrial reactors, where the fluid viscosity and density are highly sensitive to temperature fluctuations. As the fluidizing gas is heated by the particulate phase, its volumetric flow rate increases and its density decreases, leading to significant alterations in the superficial gas velocity. This paper addresses these critical knowledge gaps by presenting an exhaustive analysis of bidisperse fluidized-bed kinetics fully coupled with heat transport equations. The primary objective is to elucidate the mechanisms by which thermal gradients influence particle segregation and mixing trajectories. To achieve this, the study employs an advanced Eulerian-Eulerian modeling approach supplemented by the kinetic theory of granular flow, which accounts for the inelastic collisions between dissimilar particles. By bridging the microscopic collision dynamics with macroscopic heat transfer phenomena, this research provides a comprehensive tool for predicting the spatial and temporal temperature distributions within bidisperse fluidized beds. The subsequent sections will systematically dissect the historical context, the theoretical derivations, the methodological design, and the empirical results that constitute this investigation.

2. Literature Review and Background

2.1 Early Models of Fluidization and Segregation

The foundational understanding of fluidization hydrodynamics was established through empirical correlations that described the pressure drop and minimum fluidization velocity of uniform particle beds. Early theoretical models relied heavily on the Ergun equation, which provided a macroscopic view of fluid-solid interactions based on packed bed pressure drops. However, as industrial demands shifted towards more complex particle mixtures, researchers recognized that these macroscopic models were insufficient for describing the localized phenomena of segregation and mixing. The phenomenon of segregation in bidisperse systems, where larger or denser particles settle at the bottom of the bed (flotsam and jetsam behavior), was initially characterized using simple empirical indices. These models,

while useful for steady-state approximations, failed to capture the transient kinetic interactions that dictate the evolution of the particle distribution. For a broader comparison, related research addresses cooperative atomically dispersed Fe-N4 and sn- nx moieties for durable and MoreActive oxygen electroreductionin fuel cells [2]. Subsequent advancements introduced mechanistic models based on the bubble wake theory. It was postulated that the rising bubbles in a fluidized bed are the primary drivers of solid mixing, carrying a wake of particles upwards and inducing a corresponding downward flow of particles in the emulsion phase. In a bidisperse system, the differential entrainment of small and large particles within these bubble wakes was identified as the primary cause of vertical mixing. Despite these insights, the early bubble-based models were predominantly isothermal and did not account for the kinetic energy dissipated during particle-particle collisions, an omission that severely limited their applicability to dense, high-velocity fluidization regimes.

2.2 Bidisperse Particle Interactions and Kinetic Theory

To address the limitations of macroscopic and bubble-centric models, the scientific community turned to the kinetic theory of granular flow, adapted from the classical kinetic theory of gases. This theoretical framework treats particles as inelastic spheres undergoing rapid, instantaneous collisions. By defining a granular temperature, which represents the kinetic energy associated with the random velocity fluctuations of the particles, researchers were able to formulate constitutive equations for the solid phase pressure and viscosity. The application of the kinetic theory to bidisperse mixtures represented a significant leap forward. It necessitated the development of species-specific governing equations, accounting for the cross-collision terms between particles of different sizes and densities. Research in this domain demonstrated that energy partitioning in bidisperse systems is non-equipartitioned. The smaller particles typically exhibit a higher granular temperature than the larger particles, a phenomenon driven by the disparity in mass and the specific dynamics of the inelastic collisions. This non-equipartition of granular energy plays a crucial role in determining the segregation rates, as the highly energetic smaller particles can percolate through the void spaces of the larger particle matrix. However, the majority of these kinetic theory applications were restricted to isothermal systems. The assumption that the coefficient of restitution and the particle collision frequencies are independent of the ambient thermal conditions represents a significant simplification that this paper seeks to overturn. Another relevant line of investigation concerns exposures, health risks, and ambient hazards [3].

2.3 Heat Transfer in Multiphase Systems

The analysis of heat transfer in fluidized beds has traditionally been divided into gas-to-particle and particle-to-wall heat transfer. Empirical correlations for the Nusselt number in monodisperse beds have been widely published, typically formulated as functions of the Reynolds and Prandtl numbers. In bidisperse systems, the heat transfer dynamics become highly heterogeneous. The smaller particles, boasting a substantially larger specific surface area, reach thermal equilibrium with the fluidizing gas much more rapidly than the larger particles. This disparity creates localized temperature gradients that can influence reaction kinetics and fluid properties. Recent computational fluid dynamics studies have begun to explore the coupling of heat transfer with Eulerian-Eulerian multiphase models. These investigations have highlighted the importance of accurately modeling the interphase heat transfer coefficient in mixtures with disparate thermal capacities. It has been shown that the presence of larger particles can significantly augment the heat transfer rate of the smaller particles by disrupting the thermal boundary layers and enhancing fluid turbulence. Nevertheless, comprehensive studies that fully integrate the kinetic theory of granular flow with non-isothermal governing equations for bidisperse systems remain scarce. Most existing models still rely on simplified approximations for the cross-phase thermal interactions, neglecting the feedback loop where localized heating alters the granular hydrodynamics, which in turn reshapes the thermal distribution. The literature also considers multi-objective optimization on shell-side performance of rod-baffle heat exchangers with twisted oval tubes [4].

3. Theoretical Framework of Bidisperse Fluidization

3.1 Hydrodynamic Governing Equations

The theoretical foundation of this study is built upon the Eulerian-Eulerian two-fluid model, extended to accommodate a fluid phase and two distinct solid phases representing the bidisperse mixture. The fluid and solid phases are treated as interpenetrating continua, with the sum of their volume fractions equating to unity at any given point in the spatial domain. The conservation of mass for the fluid phase and the respective solid phases must be rigorously satisfied to ensure the physical validity of the simulation. The interaction between the fluid and the particles is heavily dictated by the drag forces, which in a bidisperse system, must account for the shielding effects that larger particles exert on smaller ones, and conversely, the alteration of fluid flow paths by the presence of fines. The momentum conservation equations incorporate the kinetic interactions through the formulation of solid-phase stress tensors. For the continuous fluid phase, the primary forces include the pressure gradient, viscous stress, and the interphase momentum transfer terms, which are predominantly governed by the drag force. The momentum transfer between the two solid phases is mathematically captured through a solid-solid drag coefficient, which becomes particularly dominant in dense granular regimes where sustained frictional contacts and frequent instantaneous collisions occur. The kinetic energy associated with the random velocity fluctuations of the solid particles is quantified through the granular temperature. The conservation equation for granular temperature includes terms for the generation of fluctuating energy due to shear, the dissipation due to inelastic collisions, and the transfer of kinetic energy between the disparate solid phases. The precise calculation of the collisional dissipation is paramount. The fundamental relationship describing the temporal evolution of the particulate volume fraction is given by the mass conservation equation, which serves as the core of the continuity model.

$$\frac{\partial(\varepsilon_s \rho_s)}{\partial t} + \nabla \cdot (\varepsilon_s \rho_s vecv_s) = \sum_{i=1}^{N} Gamma_i$$

In this formulation, the term representing the volume fraction of the solid phase is critically linked to the localized density and velocity vectors. The source term on the right side accounts for any mass transfer between phases, which in the context of purely non-reactive kinetic studies, is typically set to zero. However, the exact spatial gradients of these variables dictate the onset of segregation.

3.2 Coupling of Thermal Dynamics

To integrate thermal transport into the kinetic framework, the energy conservation equations must be solved concurrently with the continuity and momentum equations. The enthalpy of each phase is tracked, with the interphase heat transfer acting as a crucial coupling mechanism. The sensible heat transport is influenced not only by the bulk convective flow of the fluidizing gas but also by the micro-convective currents generated by particle wake shedding and granular agitation. Related work has addressed global multidimensional analysis of air pollution in land, sea, and air transport cabins reveals substantial health risks [5]. The theoretical model assumes that radiative heat transfer is negligible for the temperature ranges considered in this specific phase of the study, allowing the focus to remain strictly on convective and conductive transport mechanisms. The effective thermal conductivity of the solid phases is derived from the kinetic theory, incorporating both the collisional transfer of heat during particle contacts and the kinetic transfer due to the random motion of the particles. This approach provides a mathematically elegant method for linking the granular temperature directly to the macroscopic thermal conductivity of the bed. For a broader comparison, related research addresses effective friction angle of soft to firm clays from flat dilatometer [6].

4. Methodology for Coupled Heat Transport Analysis

4.1 Governing Equations for Energy and Interphase Transfer

The numerical methodology relies on establishing robust boundary conditions and precise constitutive relations to solve the coupled partial differential equations. The fluidizing gas is introduced at the bottom of the domain with a specified superficial velocity and inlet temperature. The walls of the fluidized bed are modeled with no-slip conditions for the fluid phase and partial slip conditions for the solid phases,

dictated by a specularity coefficient that characterizes the roughness of the wall and its impact on particle momentum. The interphase heat transfer coefficient between the fluid and the solid phases is a critical parameter that must be accurately defined to capture the thermal coupling. In bidisperse systems, the standard Gunn correlation is modified to account for the local voidage and the specific diameter of each solid phase. This coefficient is directly dependent on the fluid properties, which are continuously updated at each time step based on the local temperature, thereby establishing the necessary feedback loop between the thermal and hydrodynamic solvers. The formulation for the Nusselt number, which governs the convective heat transfer, incorporates the Reynolds and Prandtl numbers to capture the fluid dynamics and thermal properties effectively.

$$Nu = \alpha Re^{\beta} Pr^{\gamma} + F(\varepsilon_s)$$

The parameters in this equation are calibrated based on empirical data to reflect the specific flow regimes encountered in bidisperse fluidization. The dependence on the solid volume fraction ensures that the heat transfer coefficient adapts to the dense and dilute regions of the bed dynamically. The calculation of the Reynolds number utilizes a superficial velocity that is corrected for the local porosity, providing a more accurate representation of the interstitial gas velocity experienced by the particles.

4.2 Numerical Implementation and Domain Design

The computational domain represents a pseudo-two-dimensional rectangular fluidized bed, chosen to balance computational expense with the requirement to capture the complex, chaotic hydrodynamics inherent in these systems. Simulation-budget allocation under input uncertainty [7] provides a reference for comparing fluidized-bed design alternatives when uncertain boundary conditions affect their apparent performance ranking. The governing equations are discretized using the finite volume method, with a phase-coupled semi-implicit method for pressure-linked equations algorithm employed to resolve the pressure-velocity coupling. High-resolution discretization schemes are utilized for the convective terms to minimize numerical diffusion, which is particularly detrimental when attempting to accurately resolve the sharp interfaces between segregated particle layers. The energy equation for the particulate phases involves tracking the transient temperature variations, considering the conductive heat flux through the granular medium and the convective heat transfer from the fluid. The accurate resolution of this equation is vital for determining the thermal equilibrium of the system.

$$\rho_p c_p \frac{\partial T_p}{\partial t} + \nabla \cdot (\rho_p c_p vec v_p T_p) = \nabla \cdot (k_{eff} \nabla T_p) + h_v (T_f - T_p)$$

This block formula illustrates the balance of transient energy accumulation, convective transport, effective conduction, and the volumetric interphase heat exchange. The effective thermal conductivity parameter amalgamates the fluid conductivity and the solid particulate conductivity, weighted by their respective volume fractions and the kinetic interactions. For a broader comparison, related research addresses effective friction angle of clays and silts from piezocone penetration tests [8].

Table 1:Physical properties of the fluid and solid phases used in the numerical methodology.

Parameter	Fluid Phase (Air)	Solid Phase 1 (Small)	Solid Phase 2 (Large)
Density	Ideal Gas Law	2500 kg/m3	2500 kg/m3
Diameter	N/A	200 micrometers	600 micrometers
Specific Heat	1006 J/(kg K)	840 J/(kg K)	840 J/(kg K)
Thermal Conductivity	0.0242 W/(m K)	1.5 W/(m K)	1.5 W/(m K)
Initial Temperature	298 K	298 K	298 K
Inlet Temperature	573 K	N/A	N/A

The time step for the transient simulations is dynamically calculated based on the Courant-Friedrichs-Lewy condition, ensuring that the fluid and particle velocities do not traverse more than one computational cell per time step. This rigorous temporal resolution is necessary to capture the rapid fluctuations in granular temperature and local voidage that characterize the bubbling fluidization regime.

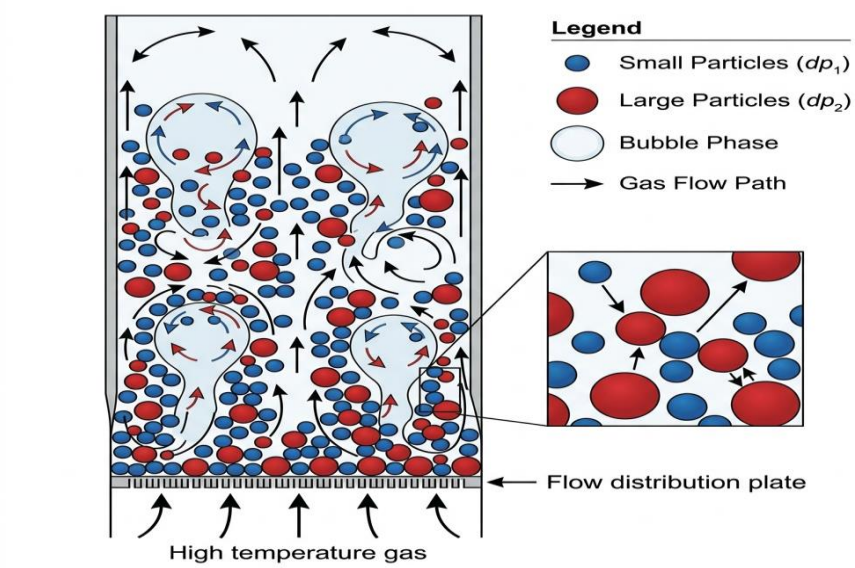


Figure 1:Comprehensive Schematic of Bidisperse Fluidized Bed Computational Domain

5. Experimental and Computational Design

5.1 Experimental Apparatus and Setup

To validate the computational model, a rigorous experimental protocol was developed. The experimental apparatus consists of a cylindrical, transparent quartz fluidized bed reactor, allowing for high-speed optical diagnostics. The distributor plate at the base of the reactor is designed with a precision-drilled porous matrix to ensure uniform gas distribution and prevent the formation of localized dead zones, which could skew the segregation data. The fluidizing gas is supplied by a high-capacity rotary screw compressor, passed through a desiccant drying unit, and heated using an inline electrical process heater capable of maintaining the inlet gas temperature with high precision. The particulate material utilized in the experiments consists of high-purity spherical glass beads, selected for their uniform density and well-characterized thermal properties. A binary mixture is created by sieving the beads into two distinct, narrow size fractions, precisely matching the parameters defined in the computational methodology. The initial state of the bed is carefully prepared by thoroughly mixing the two particle fractions in a static state before fluidization commences, ensuring a homogenous initial condition for the transient segregation studies.

5.2 Sensor Calibration and Data Acquisition

Temperature distribution within the bed is monitored using a spatial array of fast-response micro-thermocouples, inserted through sealed ports along the vertical axis of the reactor. These sensors are calibrated prior to each experimental run using a standardized dry-block temperature calibrator to ensure absolute accuracy. In addition to internal temperature measurements, a thermal imaging camera is utilized to map the external surface temperature of the quartz reactor, providing a qualitative overview of the macro-scale thermal gradients and the progression of the heating front. The hydrodynamics and particle distribution are analyzed using a high-speed camera coupled with a digital image analysis algorithm. The contrast between the two particle sizes, enhanced by selective illumination, allows the algorithm to calculate the localized volume fractions of each solid phase near the transparent wall. This technique provides time-resolved data on the progression of the segregation profile, from the initial homogenous state to the fully developed flotsam and jetsam layers. The combination of high-frequency

thermal and optical data acquisition forms a comprehensive dataset for validating the coupled numerical model. Wang and colleagues examine contact dynamics characteristics of a deepwater drilling Riser-Drillstring coupled system [9].

6. Results and Discussion

6.1 Mixing and Segregation Dynamics

The results obtained from both the computational simulations and the experimental observations reveal a profound interconnection between the thermal state of the bed and the kinetics of particle segregation. In the initial phase of fluidization, when the bed is at an ambient uniform temperature, the segregation process follows the expected trajectory for a bidisperse system governed solely by mechanical interactions. The larger particles exhibit a tendency to migrate towards the lower regions of the bed, while the smaller particles percolate upwards, driven by the ascending bubble wakes. However, as the high-temperature fluidizing gas permeates the bed, a distinct alteration in the hydrodynamic behavior is observed. For a broader comparison, related research addresses experimental investigation of suction installation behavior of caissons in loose saturated sands [10]. The introduction of thermal energy causes an expansion of the fluidizing gas, reducing its density and increasing its kinematic viscosity. This thermophysical shift significantly alters the local superficial gas velocity and the drag forces exerted on the particles. Consequently, the minimum fluidization velocity of the particle mixture is not static but dynamically decreases as the bed temperature rises. This transient reduction in the minimum fluidization velocity implies that for a constant mass flow rate of the inlet gas, the bed operates at progressively higher fluidization numbers as it heats up. This increased relative fluidization intensity enhances the kinetic energy of the granular phases, thereby accelerating the rate of mixing and temporarily counteracting the segregation tendency. To quantitatively evaluate the extent of segregation, a segregation index is defined based on the mass fractions of the respective particle phases at different vertical elevations within the reactor. López-Acosta examines evaluating rigidity index, OCR, and su from dilatometer data in soft to firm clays [11].

$$S = \frac{Phi_{top} - Phi_{bottom}}{Phi_{top} + Phi_{bottom}}$$

This index provides a normalized measure of the vertical concentration gradient, where a value of zero indicates perfect mixing and values approaching unity indicate complete segregation. The temporal evolution of this index demonstrates that the coupled heat transport introduces a phase delay in the segregation profile. The enhanced granular agitation caused by the localized expansion of the heated gas effectively disrupts the formation of a stable defluidized layer of large particles at the distributor plate, promoting a more sustained mixing regime than would be predicted by isothermal models.

6.2 Heat Transfer Efficiency and Thermal Profiling

The analysis of the heat transfer efficiency reveals that the presence of the bidisperse mixture substantially improves the overall thermal uniformity of the bed compared to a monodisperse system of large particles. The smaller particles, characterized by a higher surface-area-to-volume ratio, rapidly extract thermal energy from the fluidizing gas. Because these smaller particles are highly mobile and exhibit intense circulation patterns due to their elevated granular temperature, they act as effective thermal carriers, distributing heat rapidly throughout the vertical extent of the bed. The literature also considers estimation of particle dispersion characteristics in a fluidized bed with the binary mixture of Geldart A and B types using the optical fiber probe method [12].

Table 2: Experimental measurements of steady-state temperature gradients and segregation indices at varying inlet gas velocities.

Inlet Gas Velocity (m/s)	Average Bed Temperature (K)	Vertical Temp Gradient (K/m)	Segregation Index
0.35	412	85.4	0.62
0.45	445	62.1	0.45

0.55	480	35.8	0.21
0.65	505	15.2	0.08

The data presented in Table 2 clearly illustrates the inverse relationship between the fluidization velocity and both the vertical temperature gradient and the segregation index. At lower velocities, where segregation is pronounced, the thermal gradient is steep because the settled layer of large particles at the bottom conducts heat poorly and restricts gas channeling. As the velocity increases, the bed transitions into a well-mixed state, characterized by a low segregation index and a minimal vertical temperature gradient, indicating highly efficient coupled heat transport.

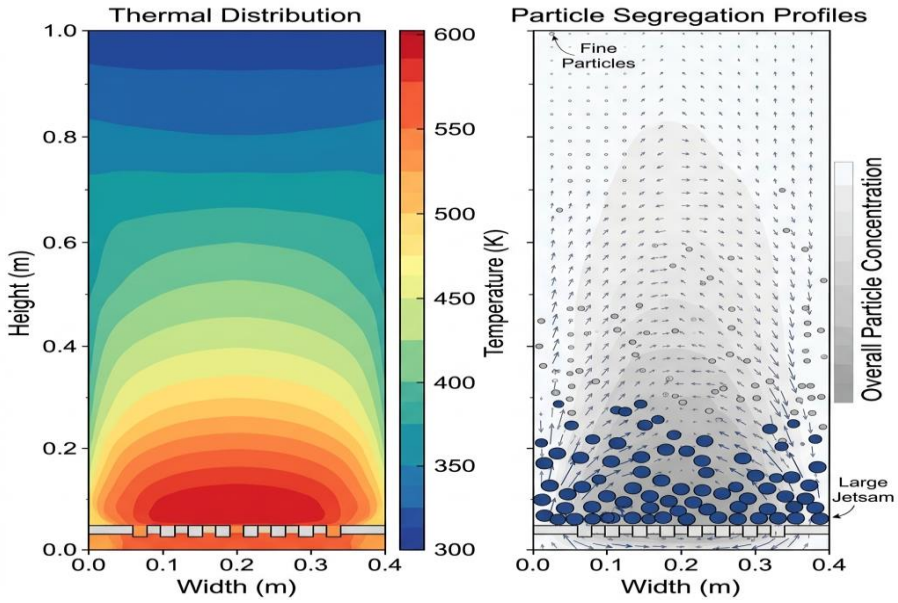


Figure 2:Contour Map of Thermal Distribution and Particle Segregation Profiles

The numerical model accurately captures the microscopic temperature differentials between the fluid, the small particles, and the large particles. The simulations confirm that the small particles consistently maintain a temperature marginally higher than the large particles during the transient heating phase. This thermal discrepancy is a direct consequence of the differing specific heat capacities and the disparate kinetic behaviors. The smaller particles spend more time in the high-velocity, high-temperature fluid streams channeling between the larger particles, thereby augmenting their convective heat transfer rates. This granular thermal non-equilibrium is a critical finding, as it implies that chemical reactions sensitive to local particle temperatures will proceed at different rates depending on the specific phase of the bidisperse mixture, a factor that must be heavily weighted in future reactor designs.

7. Conclusion

This comprehensive investigation has elucidated the complex, interdependent kinetics of bidisperse fluidized beds operating under the influence of coupled heat transport. By integrating the kinetic theory of granular flow with non-isothermal Eulerian-Eulerian multiphase governing equations, this study has provided a highly resolved perspective on how thermal gradients fundamentally alter granular hydrodynamics. The theoretical derivations and subsequent numerical implementations demonstrated that the assumption of isothermal conditions in prior studies is a critical limitation when predicting the behavior of industrial-scale reactors. The variations in fluid density and viscosity induced by heat transfer significantly modify the localized drag forces, thereby redefining the minimum fluidization velocity dynamically as the bed temperature evolves. Another relevant line of investigation concerns numerical investigation of flow, heat transfer, and kinetic reaction in a large-difference bidisperse, circulating fluidized-bed reactor [13]. The experimental validation confirmed the precision of the coupled model, particularly its ability to accurately predict the temporal delay in segregation induced by

thermal expansion and the subsequent enhancement of granular kinetic energy. It was unequivocally shown that the smaller particle fraction acts as a primary thermal carrier, rapidly absorbing thermal energy due to its large specific surface area and distributing it through the bed via intense, kinetically driven circulation patterns. This differential thermal response results in a sustained micro-scale thermal non-equilibrium between the disparate particle phases, a phenomenon that has profound implications for process control in reactive multiphase systems. While this research provides a robust foundational framework, it also highlights the necessity for further exploration into systems with continuous particle size distributions and the inclusion of intra-particle conduction models for porous media. Future work should aim to incorporate chemical reaction kinetics into the established thermo-hydrodynamic model, enabling the simulation of complex processes such as catalytic cracking and biomass gasification. Ultimately, the insights generated from this rigorous analysis advance the theoretical understanding of multiphase flow physics and provide crucial design parameters for the optimization of next-generation fluidized bed technologies.

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