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Review

Review of entrainment correlations in gas–solid fluidization

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HIGHLIGHTS

- Review of applicability of entrainment correlations to Geldart Groups A and B.
- Monodisperse, binary, and continuous particle size distributions (PSDs) considered.
- Discrepancies among correlations span several orders of magnitude.
- Unphysical phenomena predicted include preferential elutriation of larger particles.
- Poor predictive capability underscores need for more physically-based models.

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ABSTRACT

Despite the abundance of entrainment correlations in gas–solid fluidization made available in the past few decades, the discrepancy between empirical prediction and experimental data has been noted to be up to a hundredfold in some cases. Hence, a comprehensive review of the available correlations is warranted, with the goal of extracting the underlying physics giving rise to the disparities, and thereby providing insights towards an enhanced understanding of entrainment. This review addresses a comprehensive spectrum of particle systems, ranging from monodisperse to binary to continuous particle size distribution (PSD) systems for the more predominant Geldart Groups A and B classifications. Three key observations are highlighted. First, comparisons of the predicted entrainment values among available correlations reveal discrepancies spanning several orders of magnitude, with the maximum being 20 orders of magnitude, evidencing that available empirical correlations do not extrapolate well beyond the scope of tested parameters. Second, unphysical phenomena predicted include qualitative discordance on the shapes of the elutriated PSDs, the most notable of which is the anomaly whereby larger particles are preferentially elutriated. Third, whether a particular correlation was developed for a specific Geldart Group or for monodisperse and/or polydisperse systems seems inconsequential to giving better predictions even when appropriately applied to the particular subset. These observations underscore the need for more physically-based models to enable a more accurate prediction of entrainment and elutriation phenomena.

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Nomenclature

A	cross-sectional area of fluidizing column, m^2
Ar	$\frac{gd_{pi}^3\rho_g(\rho_p-\rho_g)}{\mu^2}$ = Archimedes number of size i particles, –
C_d	drag coefficient, –
D_c	inner diameter of fluidizing column, m
d_{pi}	mean particle size of size i particles, m
d_b	equivalent bubble size at bed surface, m
Fr_i	$\frac{(U_g-U_{ti})^2}{gd_{pi}}$ = particle Froude number of size i particles, –
g	gravitational acceleration, m/s^2
H	freeboard height, m
H_c	height of fluidized bed column, m
H_s	height of settled fluidized bed, m
$K_{i\infty}$	elutriation rate constant, kg/m^2s
Re_p	$\frac{U_g d_{pi}\rho_g}{\mu}$ = particle Reynolds number of size d_{pi} particles evaluated at U_g, –
Re_i	$\frac{(U_g-U_{ti})d_{pi}\rho_g}{\mu}$ = particle Reynolds number of size d_{pi} particles evaluated at $U_g - U_{ti}$, –
Re_{ti}	$\frac{U_{ti} d_{pi}\rho_g}{\mu}$ = particle Reynolds number of size d_{pi} particles evaluated at U_{ti}, –
Re_D	$\frac{U_g D_{col}\rho_g}{\mu}$ = flow Reynolds number, –
T	temperature, K
U_g	superficial gas velocity, m/s
U_{mfi}	minimum fluidization velocity of size d_{pi} particles, m/s
U_{ti}	terminal velocity of size d_{pi} particles, m/s
x_i	mass fraction of size d_{pi}, –
x_{ie}	mass fraction of size d_{pi} in elutriated material, –
Symbols	
ε_{mf}	voidage under minimum fluidization condition, –
μ_g	gas viscosity, kg/ms
ρ_g	gas density, kg/m^3
ρ_p	particle density, kg/m^3
ϕ	particle sphericity, –

1. Introduction

One of the first correlations for entrainment was published in 1955 [1]. Since then, an abundance of entrainment correlations has been made available [2–8]. Unfortunately, due to the use of empirical constants in the absence of a more fundamental understanding of such processes, the discrepancy between empirical prediction and experimental data is up to a hundredfold in some cases [4,7]. Good predictive capability of entrainment values is critical for the technical and economic success of a fluidized bed application, because the optimal design of gas–solid separators like cyclones and filters [4,8] to minimize bed material loss hinges on such a priori estimates. Hence, a comprehensive review of the available correlations is warranted, with the goal of extracting the underlying physics giving rise to the disparities, and thereby providing insights towards enhanced understanding of entrainment and elutriation. It is worthwhile to note three items regarding the scope of this review: (i) new experimental data is not presented, since one of the key failings of empirical entrainment correlations appears to be that the underlying experimental data is only relevant to the narrow set of conditions it was taken at and may not be appropriate for extrapolation, (ii) recommendation on which of the correlation is most relevant is beyond the scope of this review, since such clarity is not possible without more research work into better physical understanding and description of the entrainment phenomenon, and (iii) recommending rules-of-thumb on reactor design is not part of this review.

The difference in definition of the terms entrainment and elutriation needs clarification. Although both generally refer to the flow of solids out of fluidized beds, they cannot be used interchangeably especially for polydisperse (i.e., the presence of a range of particle sizes and/or particle density) systems. On one hand, entrainment refers to the overall flux of solids carried out of the fluidized bed by gas; on the other hand, elutriation refers to the classifying effect of fluidized bed entrainment, specifically characterizing the selective removal of particles of individual sizes from the fluidized bed [4,8]. In other words, while entrainment flux is equal to elutriation flux when only a single species is present as is the case for monodisperse systems, entrainment flux is greater than the elutriation flux for each species in the presence of multiple species for polydisperse systems.

Physically, entrainment in the freeboard is widely acknowledged as being initiated by the role of bubbles in ejecting particles upwards [8–10], although different schools of thoughts exist on whether particles ejection stems from the bubble nose or bubble wake [8]. The different origins have been reported to cause discrepancy of up to one order of magnitude in the entrainment flux at the bed surface [8], due primarily to differences in (i) particle size distribution above the bed surface, and (ii) particle dispersion in the freeboard [11,12]. Regarding (i), the bubble nose is observed to preferentially eject fine particles, whereas the bubble wake ejects both fine and coarse particles. With respect to (ii), the bubble nose aids dispersion of particles after being ejection from the bed surface, whereas the bubble wake ejects particle clusters into the freeboard. As particles travel upwards in the freeboard, some particles will return to the dense bed while others will continue the upward trajectory, thereby resulting in an exponentially decreasing entrainment or particle concentration profile with respect to height. For more details on the entrainment phenomenon, the interested reader is referred to the book chapters [2,4,6,8].

Experimental efforts targeted at quantifying entrainment and elutriation have been pursued, resulting in a broad spectrum of empirical constants rooted in data-fitting and varying emphasis on different system or operating parameters being presented. Modeling efforts have also progressed in parallel. As early as in the 1950s, simplified models developed based on particles behaving independently [10,13] proved insufficient in explaining observed phenomena like the entrainment of particles with terminal velocities greater than the operating superficial gas velocities ($U_t > U_g$) [14,15], and decreasing entrainment and solids concentration with increasing height. To date, due to the complexity of gas–solid flows, particularly with respect to inter-particle cohesion and hydrodynamic clustering effects, models continue to rely on assumption-based simplified physical descriptions. Experiments and models are complementary tools: while experimental results provide data for validating models, models are conversely necessary to extract the physics underlying the observed flow phenomena [16]. Accordingly, the generation of an understanding of the physics underlying available empirical entrainment correlations is necessary in order to validate and improve models; generating such an understanding is an overall aim of this work.

In the current review, K_∞ refers to the total entrainment flux above transport disengagement height (TDH), while $K_{i\infty}$ refers to the elutriation flux of individual species i above TDH. Specifically, K_∞ and $K_{i\infty}$ are related by the equation $K_\infty = \sum_i^x K_{i\infty}$, where x_i is