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Research paper

# Effect of freeboard deflectors on the temperature distribution in packed beds

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## HIGHLIGHTS

- The influence of freeboard deflectors on the temperature distribution in packed beds is studied.
- Methods applied include CFD modelling, validation against experimental data and empirical fits.
- The impact of deflectors largely depends on the heating mode (wall versus air stream; 100–400 °C).
- Stronger effects occur on wall temperature (in the freeboard) compared to packed bed temperature.

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## ABSTRACT

Freeboard deflectors have been applied in solid fuel combustors but little investigation has been undertaken to understand their impact on packed beds. This paper studies the influence of a deflector above a packed bed by implementation of a three-dimensional Computational Fluid Dynamics (CFD) model of a porous media. Through validating the model against experimental data, the effects of a freeboard deflector on the radial and axial temperature profiles is studied for a temperature range typical for drying and volatile release in biomass combustion (100–400 °C). Numerical results indicate that the deflector influences wall temperatures as well as temperatures along the freeboard but this is dependent on the mode of heating and emissivity of the deflector.

## 1. Introduction

High surface-area to volume ratio associated with packed beds exists in a variety of engineering applications [1]. These applications include chemical reactors [2–6], fixed bed combustors [7–10], particle dryers [11–16], air dehumidifiers [17], air conditioning [18], heat storage systems [19–21] and heat exchangers [22,23]. Optimising the heat transfer characteristics of packed beds plays a pivotal role in achieving specific design and performance gains in the abovementioned applications. Packed beds remain the subject of ongoing investigation, where Table 1 presents a summary of several experimental studies to resolve their heat transfer coefficients [24–29]. Nevertheless, a number of unresolved challenges persist. Such challenges include, a better understanding on the variation of the effective thermal conductivity over a range of Reynolds (*Re*) numbers and temperatures, the influence of wall effects on the axial temperature distributions (within the bed) and the effects of porosity. The task of resolving these factors in relation to modelling particle drying and fixed-bed combustion is exacerbated by the prevalence of studies with either extremely low Reynolds numbers [30–32]; the use of glass, metallic or other non-drying particles [2]; poorly defined boundary condition data [33,34] and/or that most packed bed reaction models are simulated as porous media [14,35,36].

In combusting packed beds, such as those appearing in high temperature processes involving solid particle combustion, the residence time and radiation effects of the freeboard (space above the packed bed) are important. Biomass combustion has been investigated on laboratory-scale fixed beds to better comprehend the thermal conversion processes [37,38]. In this context, heat transfer rates inside packed beds limit evaporation rates [12] and other sub-processes such as volatile release. In counter-current fixed bed combustion [39], whereby ignition occurs in the top

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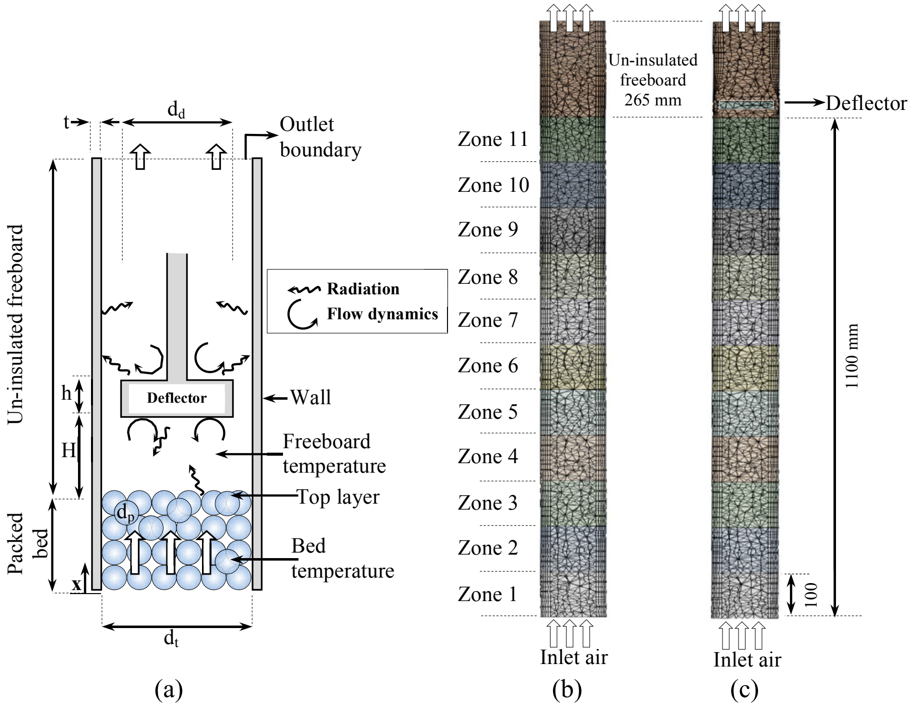
**Table 1**
Summary of experimentally derived heat transfer relationships in packed beds.

| Author (s) | Equation | Packed bed |
|---|---|---|
| Calderbank and Pogorski [24] | $Nu = 4.21Re^{0.365}$ | Cylindrical packed bed, $8 < d_t/d_p < 16$, aluminum spheres |
| Yagi and Kunii [26] | $Nu = 15 + 0.029Re$ | Annular packed bed, $3.9 < d_t/d_p < 51$, glass beads |
| DeWasch and Froment [27] | $Nu = 12.5 + 0.048Re$ | Cylindrical packed bed, $d_t/d_p = 176$ |
| Li and Finlayson [28] | $Nu = 0.178Re^{0.790}$ | Cylindrical packed bed, $3 < d_t/d_p < 5$, celite spheres |
| Demirel et al. [29] | $Nu = 0.197Re^{0.718}$ | Rectangular packed bed, $3 < d_t/d_p < 5$, polyvinyl chloride Raschig rings |
| Demirel et al. [29] | $Nu = 0.217Re^{0.756}$ | Rectangular packed bed, $4.5 < d_t/d_p < 7.5$, expanded polystyrene spheres, |

layer of the packed bed and propagates downwards, the char reaction zone at the surface of the fixed bed is typically 50 mm thick [40]. Therefore, operational or design (geometrical) features that influence the heat transfer in the upper layers of combusting packed beds may also affect the high temperature (post-bed) reactions occurring in the freeboard. In commercial-scale combustors, deflectors placed in the freeboard have been employed to reduce particulate matter and influence gaseous species emissions [17,41]. These devices also enhance performance by reducing flame radiation into the exhaust stack by affecting the heat transfer in the freeboard [17,42]. Fig. 1a shows a freeboard deflector mounted above a packed bed in a laboratory-scale fixed bed combustor. Whilst no systematic studies into the effects of freeboard deflectors has been made, published work [43] indicates that wall temperatures and flow dynamics in the post-bed (freeboard) region affect the migration of dust, fly ash, soot and other Hydrocarbon (HC) formation.

In non-combusting packed beds, where drying from heat transfer is the primary objective, the pressure drop can be determined along the axial direction of the packed bed [44,45]. However, other factors which may affect the heat transfer in drying packed beds include the axial and radial temperature distributions. Therefore there is a focus on the requirement to attain suitable effective thermal conductivity [3,25,26,32,46,47] of the heat transfer process; some correlations for the metal-air, glass-air and catalyst-air systems have been proposed.

Although numerous numerical studies exist for the heat transfer and flow characterisation of packed beds [2,34,36,48–51], the available literature does not contain analysis into the effect of freeboard deflectors on the axial pressure drop and temperature distribution, particularly in the uppermost bed layers and freeboard regions. Whilst the availability of powerful CFD techniques can be used to effectively predict the performance of thermo-fluid systems, the application of CFD to packed beds remains challenging. The treatment of packed beds in many commercially available CFD codes considers them as porous media, whereby effective thermal conductivity ($K_e$) is calculated as a weighted average of the solid ($K_s$) and gaseous phases ($K_f$) that uses the porosity (void fraction) of these phases [52], respectively. The application of this effective thermal conductivity, albeit for its simplicity, precludes the actual heat transfer processes that may be occurring between contacting solid particles and in the voids of the packed beds where fluid flows around the solid particles. An alternative approach to circumvent the problem associated with the porous-media is to physically track the individual solid particles in packed beds [33,48,53]. The computational demands of such an approach are large and as a result packed beds are mostly treated as relatively shallow layers to limit computational demands. Consequently, flow dynamics and



(a) (b) (c)

**Fig. 1.** **(a)** A freeboard deflector mounted above a packed bed; **(b)** CFD Model-I with 265 mm freeboard used to validate against experimental data [55] and **(c)** CFD Model-II with 265 mm freeboard and deflector ($d_d$ = 36 mm, h = 10 mm).