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ESTIMATION OF THE AXIAL DISPERSION COEFFICIENT IN FLUIDISATION - AN APPROACH BASED ON ISOTROPIC TURBULENCE

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Abstract: The coefficient of axial dispersion of the liquid phase in a liquid-solid fluidized bed is determined by applying isotropic turbulence theory to velocity fluctuation measurements obtained by laser anemometry at the top of the bed. The experiments were conducted using glass particles with three different diameters, fluidized by water. The calculation method used, which is a first for the continuous phase of the fluidized bed, demonstrates that the results of the study qualitatively match the data from the literature.

Keywords: Liquid-solid fluidization, Laser Doppler Anemometer, Isotropic turbulence, Liquid axial dispersion, Bed voidage.

INTRODUCTION

Liquid-solid fluidized beds (LSFB) are increasingly favored in diverse biological process applications, such as fermentation and waste water treatment (Tang & Fan,1990). For the design and optimization of these systems, a good understanding of the mixing between the phases is essential. Since 1960**,** researchers have thoroughly examined the behaviour of individual phases within LSFB (Manjusha, 2017). Several studies have been conducted on the dispersion of solid and liquid phases in fluidized-bed systems. The main methods used for tracer injection in these studies were the impulse function and the concentration sine wave. Moreover, most of the experimental results were analyzed on the basis of the diffusion model. Some of these studies indicate that the axial dispersion coefficient of the solid phase (Handley et al.(1966); Carlos & Richardson (1968); Willus (1970); Limtrakul.S et al. (2006), For liquid phase (Tang & Fan(1990); Chung & Wen (1968); Asif (1991)) increases monotonically with the superficial fluidization velocity or bed porosity. Conversely, other research indicates the presence of a peak at a porosity ranging between 0.6 and 0.7 for both the solid phase (Al-Dibouni & Garside, 1979), Yutani (1983), Kang et al.(1990), and the liquid phase (Kikuchi et al., 1984); Sang (1989).

Fluctuations in the velocity of the liquid phase are due to the movement of solid particles in the bed and contribute to macroscopic mass transfer, which occurs in parallel with the microscopic diffusive mass transfer caused by concentration gradients within the bed (Asif, 1991). The combined effects of these mass transfer mechanisms are quantified in terms of the dispersion coefficient, which indicates the degree of mixing of fluids in the bed (Asif, 1991). In this work, we have used the experimental data of the liquid phase velocity fluctuations obtained in our previous work (Kechroud et al., 2010) to quantify systematically the axial dispersion of the liquid phase in an LSFB. For the first time, to the best of our knowledge, the dispersion coefficient is determined utilizing the theory of isotropic turbulence. To do this, we analyze liquid phase velocity fluctuations measured by laser anemometry at the bed surface (Kechroud et al., 2010). Our review of literature indicates that Limtrakul et al. (2005) are the only researchers known to have applied the theory of isotropic turbulence to examine solid phase mixing in an SLFB system. By comparing our results with those in the literature, we will highlight, as much as possible, the similarity between the dynamics of liquids and solids.

NOMENCLATURE

D_L: dispersion coefficient of liquid phase, m/s^2
Gravitational acceleration, m/s2
u(n): local axial liquid velocity, m/s
$\bar{u}$: mean of u(n), m/s
$R_L(t)$:autocorrelation coefficient
T_L: eulerian integral time scale, s
U superficial liquid velocity, m/s
U_{mf} minimum fluidization velocity, m/s
U_t terminal velocity, m/s

Greek letters

ε: average void fraction of bed
ε_{mf}: minimum average void fraction of bed
σ : root mean square of time series signal u(t), u(n), m/s
μ: liquid viscosity, kg/m s
ν: solid fraction of bed
ν′: root mean square of solid fraction
ρ_f: liquid density, kg/m^3
ρ_p: particled density, kg/m^3

EXPERIMENTAL DETAILS AND ANALYSIS METHODS

Experiments

The experimental set-up (figure 1) is the same as that used in our precedent work (Kechroud et al., 2010). The test column is made of plexiglas, with an internal diameter of 9.3 cm and a height of 2 m. A

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millimeter ruler is fixed along the entire length of the column to measure the bed height, which is a crucial parameter in calculating fluidized bed porosity (ε). The selected distribution system ensures uniform liquid distribution (Kechroud, N,2000).

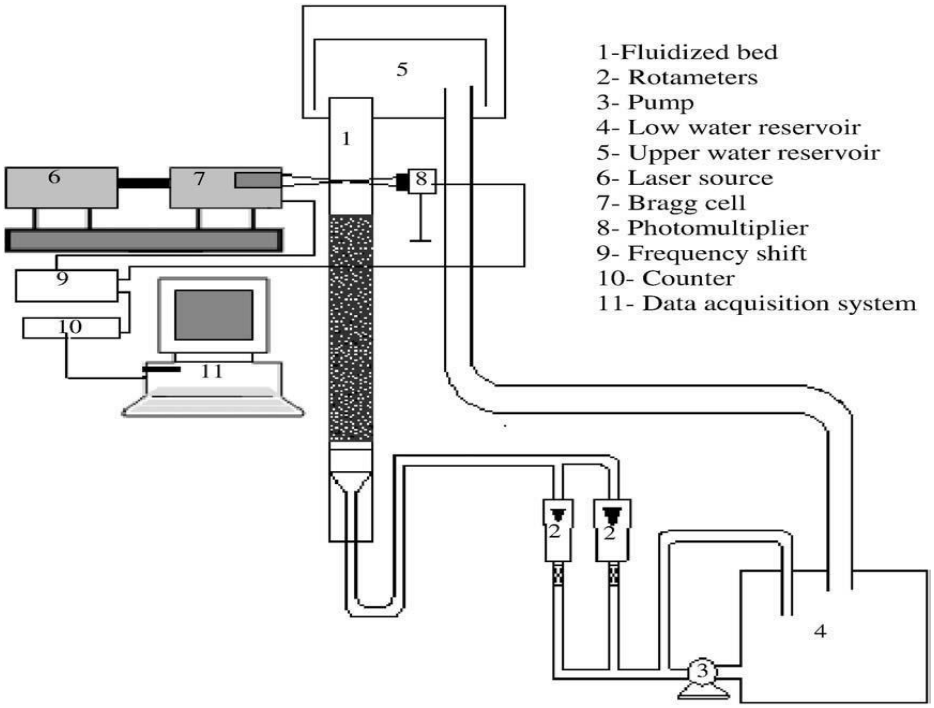

Fig. 1. Schematic of the fluidized bed apparatus.

The properties of the solid particles used, the range of flow rates covered for each bead size, and experimental values for bed porosity and liquid velocity under minimum fluidization conditions (Kechroud et al., 2010) are summarized in Table 1.

Table 1.

Properties of particles used in experiments (Kechroud et al., 2010)

Material	d_p(mm)	ρ(kg.m^{-3})	U_{mf}(cm.s^{-1})	U(cm.s^{-1})	ε
Glass	2	2554	2.45	0.88-12.25	0.4-0.81
	4	2564	4.35	1.59-19.7	0.43-0.81
	8	2595	7.8	2.8-19.5	0.44-0.7

Analysis Methods

Analysis of turbulence parameters is essential to understanding the hydrodynamic behaviour of fluidized-bed systems. Hence, it is possible to study Root-Mean-Square velocities, Eulerian autocorrelation, Eulerian integral time scales, and the coefficient of dispersion of the liquid in the bed, based on instantaneous velocities and mean velocities of the liquid phase recorded over time.

Root mean square velocity(rms)

Fluctuations in axial velocity can be used to quantify turbulence in the liquid phase.

L and u (n) be the velocity time series, the RMS of axial velocity fluctuations is estimated by

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(u(n) - \bar{u})^2} \quad (1)$$

With the mean:

$$\bar{u} = \frac{1}{N}\sum_{n=1}^{N} u(n) \quad (2)$$

Coefficient of dispersion

The coefficient of dispersion of the liquid phase at the column axis can be obtained from isotropic turbulence theory, which was first applied by Taylor (Hinze, J.O.,1973):

$$D_L = \overline{v'^2}.T_L \quad (3)$$

v' is the Eulerian fluctuation velocity, TL is the Eulerian integral time scale, it is the time during which $v'(t)$ is correlated with itself [6]. T_L is defined by the following expression (Limtrakul.S et al., 2006):

$$T_L = \int_{\circ}^{\infty} R_L(\vec{a}, t')dt' \quad (4)$$

Where the autocorrelation coefficient $R_L(t)$ is defined as :

$$R_L(\vec{a}, t') = \frac{\overline{v'(t)\,v'(t+t')}}{\overline{v'^2}} \quad (5)$$

$\overline{v'^2}$ is the mean of the square of the eulerian fluctuating velocity in the direction under

consideration (the square of the RMS velocity). When the integral Eulerian time scale o btained from the autocorrelation coefficient by equation 3 has a negative value, it can be calculated from the first moment (Devanathan, N, 1971):

$$T_L = \frac{\int_0^\infty t' \left| R_L(t') \right| dt'}{\int_0^\infty |R_L(t') dt'|} \quad (6)$$

The autocorrelation of Eulerian fluctuating velocities is obtained from this expression:

$$\overline{v'(t)\, v'(t+t')} = \frac{1}{N} \sum_{i=1}^{N} v'(t)\, v'(t+t') \quad (7)$$

Dispersion coefficient estimation

To measure the coefficient of dispersion of the liquid phase, we computed the autocorrelation function, which expresses the relation of earlier to later values in the time series (Kechroud et al., 2010) for each operating condition. To reduce the variance of the autocorrelation function and allow smoothing of these curves, the entire time series is divided into segments of equal duration (Kechroud et al., 2010). Subsequently, the autocorrelation function is computed for each segment. The averaged autocorrelation function is therefore obtained. To determine the Eulerian integral time scale, we integrated the time correlation curve of the Eulerian velocity. The analysis reveals that Eulerian integral time scale values may be negative. In this case, we applied equation (6), as suggested by Devanathan (1971). Autocorrelation function calculations are performed using Matlab toolboxes (Kechroud et al., 2010). As illustrated in Figure 2, we have presented the autocorrelation functions and smoothed autocorrelation functions obtained for particles with diameters of 2mm, 4mm, and 8mm, each corresponding to porosities of 0.6, 0.81, and 0.45, respectively.

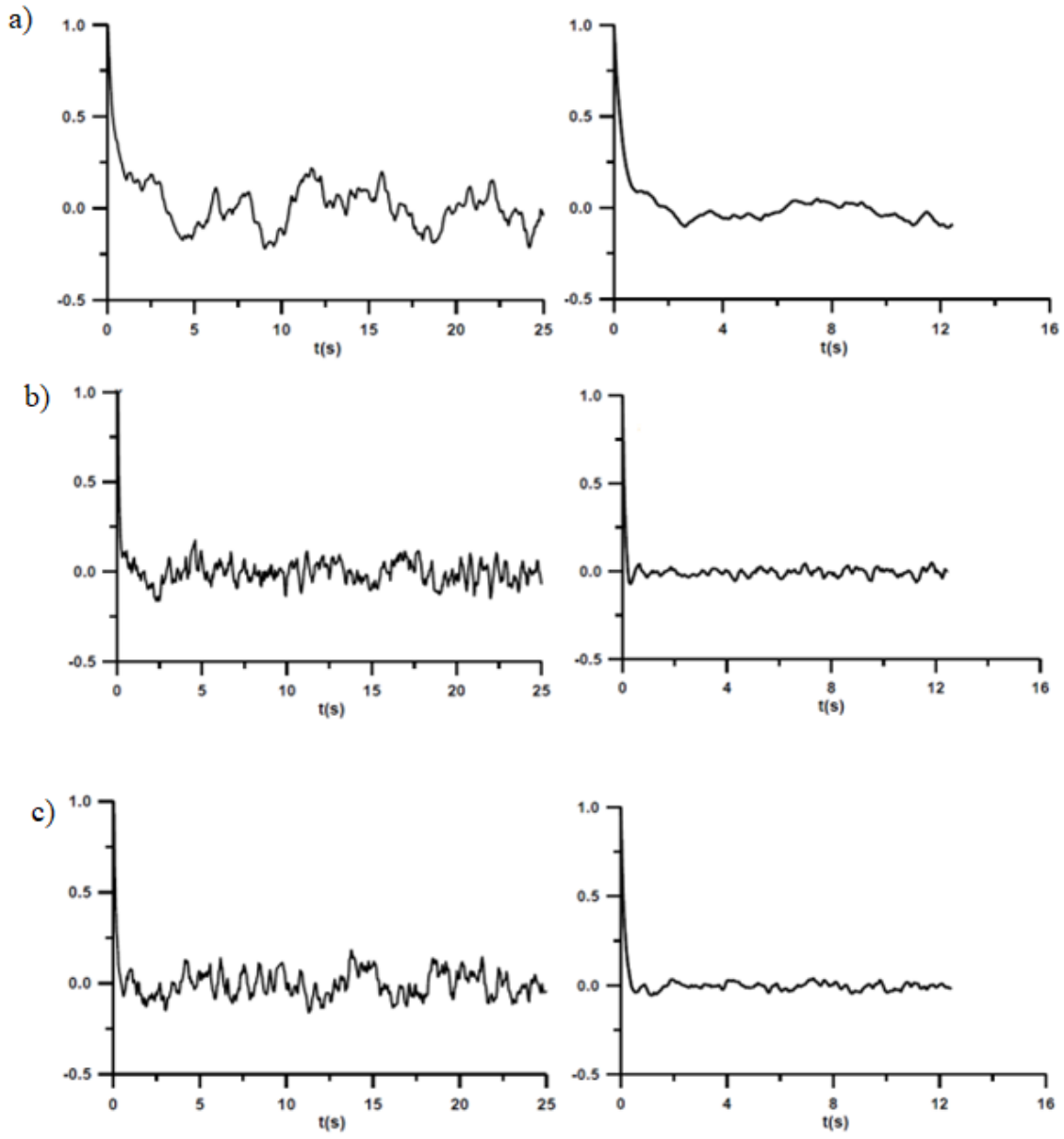

Fig. 2. Autocorrelation function and smoothed averaged autocorrelation of fluctuating velocity. a) :dp = 2 mm, ε=0.60 ; b) : dp = 4 mm, ε =0.81 ; c) : dp = 8 mm, ε=0.45.

RESULTS AND DISCUSSION

Effect of liquid velocity on axial dispersion coefficient

Figure 3 shows that the axial dispersion coefficient of the liquid phase (D_L) increases with flow velocity (U). However, there is no effect of particle size on D_L values under these experimental conditions. The same figure shows the experimental results of Chung & Wen (1968), who studied the fluidization of aluminum and glass particles by water in a cylindrical test column with an ID of 5 cm. Chung & Wen (1968) analysed the effect of particle diameter ranging from 2 mm to 6.4 mm, particle density varying from 1.3 g/ml to 7 g/ml, fluid velocity varying from Re = 51 to 1286, and bed porosity on the coefficient of dispersion. It should be noted that our experimental values are lower than those obtained by these authors. We also reproduce in the figure 4, the experimental data of Asif (1991), in the absence of any influence of the distributor, the author determined the values of the dispersion coefficient of the liquid phase *DL* in a bed of polystyrene particles (dp = 2.6 mm and ρ_p = 1.05 g / ml), polypropylene particles (dp = 2.2 mm and ρ_p = 1.61 g / ml), and glass beads (dp = 3 mm and ρ_p = 2.6 g /ml), fluidized by the tap water.

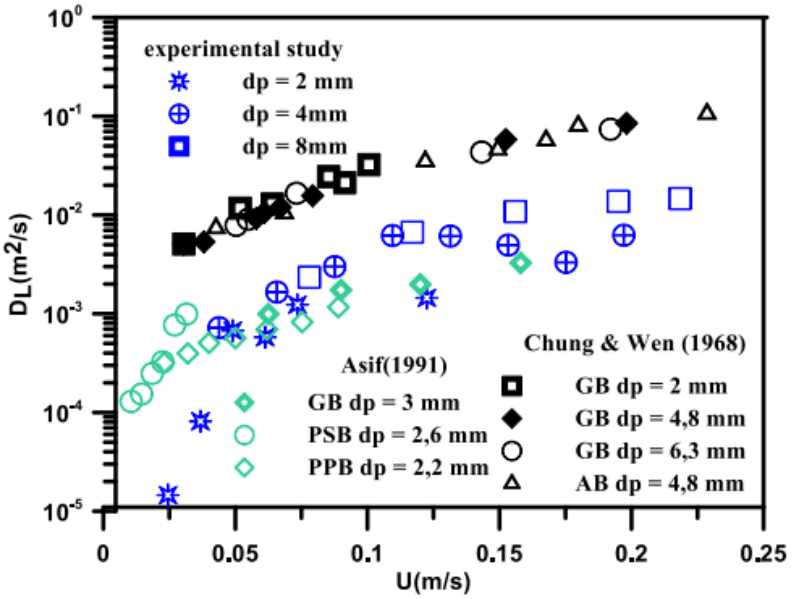

Fig. 3. Effect of liquid velocity on the coefficient of dispersion.

Effect of bed voidage on axial dispersion coefficient

The effect of bed voidage (or porosity) on the dispersion coefficient is illustrated in Figure 4, where D_L is shown to increase with particle size. For the same bed voidage, the highest terminal particle velocity has a higher D_L coefficient. According to Behin &Tahereh (1911), this is to be expected since a higher relative liquid velocity is required to maintain a given porosity of the particle bed at a higher terminal velocity. As a result, greater turbulence is generated, leading to greater particle mixing. For the three diameters studied, a maximum bed voidage appears at a value between 0.6 and 0.7. Figure 5 compares our experimental results with those presented by Kikuchi et al.(1984), who measured the coefficient of axial dispersion for polystyrene and glass particles with diameters ranging from 0.2 to 1.7 mm, fluidized by water in a cylindrical column 1.7 m high and 3.4 cm in internal diameter. According to these authors, the bed voidage has a particular effect on the evolution of the axial dispersion coefficient. Indeed, their results show a maximum for porosities between 0.7 and 0.8.

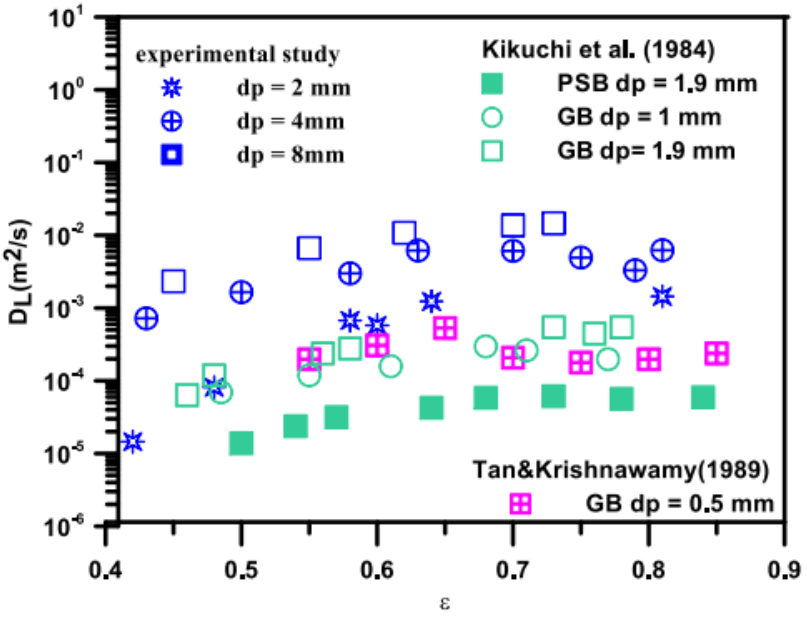

Fig. 4. Effect of bed porosity on dispersion coefficient.

The results obtained by Kikuchi et al. (1984) are qualitatively similar to those of the present study. However, their experimental values, which range from 0.8 to 6 cm^2/sec, are different from those obtained in the present study. Tan & Krishnawamy (1989) used impulse response techniques to study the effect of liquid density on axial dispersion in fluidized beds. The authors studied the fluidization of glass particles of 0.5 mm diameter by KBr solutions with densities ranging from 0.995 g/cm^3 to 1.30 g/cm^3, in a column with an internal diameter of 5.15 cm. Their results showed the existence of a D_L maximum at a bed voidage of around 0.60 to 0.65. For illustrative purposes, we have reproduced the results obtained by these authors for a liquid density of 1.3.

COMPARISON TO LITERATURE DATA OF THE SOLID PHASE DISPERSION COEFFICIENT

In this section, we have compared our experimental results for the axial dispersion of the liquid phase with the results for the solid phase axial dispersion obtained by Aldibouni& Garside (1971) and Kang et al. (1990). Experimental results of Kang et al. (1990) show that the coefficient of dispersion calculated using the relaxation method increases with porosity (Figure 5), reaching a maximum value between 0.6 and 0.7.

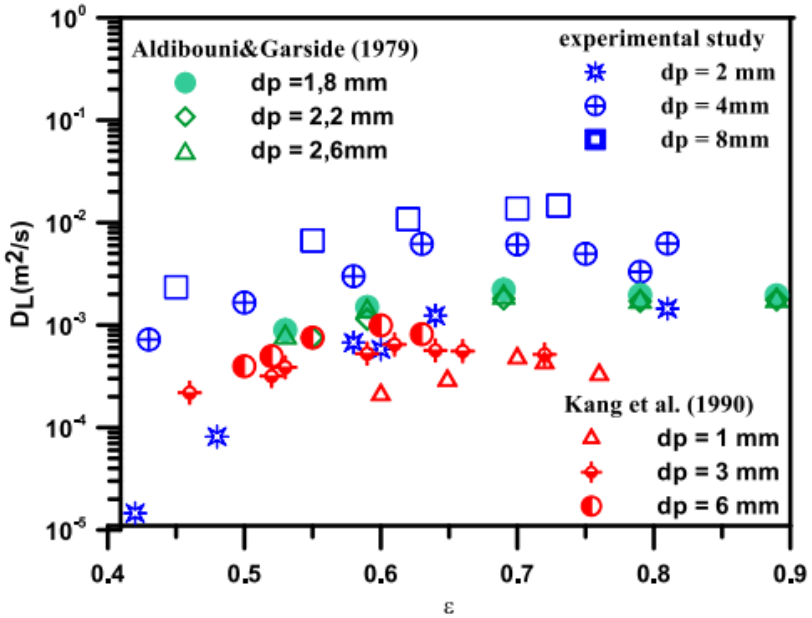

Fig. 5. Axial dispersion of solid and liquid phases as a function of bed voidage.

The authors note that the porosity value for which the maximum is reached decreases with fluidized particle diameter, which the authors attribute to a smaller expansion of larger particles than that of smaller ones. Diffusivity increases with fluidized particle size. A similar trend was observed

by Aldibouni & Garside (1971). In our previous work (Kechroud et al., 2010), we demonstrated that there is an analogy in behavior between solid-phase and liquid-phase dynamics, through the comparison of velocity fluctuations, spectra, and frequency scales of coherent motions of the two dynamics.

CONCLUSION

Isotropic turbulence theory is used to quantify the coefficient of axial dispersion at the outlet of a water-fluidized glass particle bed. In view of the results obtained, we conclude that, firstly, the coefficient of dispersion, D_L, increases with flow rate. However, there is no effect of particle size on D_L values under these experimental conditions. Secondly, D_L increases with particle size, reaching a maximum value at a porosity between 0.6 and 0.7 for the three diameters studied. The two phases of the fluidized bed have similar behavior. Additional tests are required to obtain more information by varying the physical-chemical properties of the two phases of the fluidized bed.

AUTHORS CONTRIBUTIONS

Conceptualization, NHM, HB, NK and HT; methodology, NHM, NK; data collection NHM, GH , NK; data validation, NHM, NK, data processing NHM, GH; writing—original draft preparation,NK, NHM; writing—review and editing, NHM.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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