Powder Technology 206 (2011) 312–321

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Validation of the Langevin particle dispersion model against experiments on turbulent mixing in a T-junction

A. Dehbi [a,*], F. de Crécy [b]

[a] Laboratory for Thermal-Hydraulics, Paul Scherrer Institut, Villigen 5232, Switzerland

[b] Laboratoire de Mécanique des Fluides et d'Acoustique, Ecole Centrale de Lyon, 69130 Ecully, France

ARTICLE INFO

Article history:
Received 12 July 2010
Received in revised form 14 September 2010
Accepted 26 September 2010
Available online 1 October 2010

Keywords:
Lagrangian particle tracking
Continuous Random Walk
CFD
DES
Mixing

ABSTRACT

The fluctuating fluid velocities seen by particles entrained in a turbulent fluid have recently been modeled using a stochastic model based normalized Langevin Continuous Random Walk (CRW). This model has been quite successful in predicting particle dispersion in mildly complex flows. In the present study, we aim at validating the CRW model further against data collected in a challenging 3D geometry. We consider turbulent fluid mixing downstream of a T-junction using a hybrid Euler–Lagrange approach whereby tracer particle trajectories are computed and mixing of the streams deduced from the relative concentration of particles originating from the two inlet branches of the Tee. In a first simulation, RANS Reynolds Stress Model (RSM) is used to obtain the mean flow field, whereas the fluid fluctuations are specified from a CRW. Simulation results are compared to experimental data on mixing of two isothermal streams consisting of tap and de-ionized water, respectively. It is found that RSM-CRW yields strong under-prediction of the mixing. Closer look at the results shows that the Reynolds stresses, which are required inputs to the CRW, are poorly predicted with RSM. Detached Eddy Simulations (DES) are subsequently performed to provide the mean flow field, and the DES-CRW model predictions are found to compare quite well with the experimental data.

1. Introduction

Particulate mixing and transport in turbulent flows is ubiquitous in a vast array of domains which deal with, e.g. environmental, industrial, or chemical applications. It is therefore of great interest to have numerical simulation tools that allow an accurate description of particle transport in relatively complicated geometries. Two families of methods are available to treat particle dispersion in turbulent flows: Eulerian and Lagrangian. In the Eulerian or "two-fluid" approach, particles are regarded as a continuous phase for which the averaged conservation equations (continuity, momentum and energy) are solved in similar fashion to the carrier gas flow field [1]. The Eulerian approach is optimally used for denser suspensions when particle–particle interactions and particle feedback on the flow cannot be ignored. The two-fluid Eulerian approach faces however challenges especially at boundaries where the solid phase may be removed or reflected. In addition, the specification of inter-phase exchange rates and closure laws is an especially difficult task.

On the other hand, the Lagrangian approach [2] treats particles as a discrete phase which is dispersed in the continuum. The particle motion is naturally deduced from Newton's second law, allowing one to include all the relevant forces that are significant (drag, gravity, lift, thermophoretic force, etc.). Although computationally intensive because it involves tracking a large number of particles, the Lagrangian particle tracking (LPT) approach is easier to implement and interpret. In this investigation, the LPT methodology is used, along with the assumption that the dispersed phase is dilute enough not to affect the continuous flow field (one-way coupling).

In laminar flows LPT involves very few assumptions and approximations, and is hence able to accurately predict particle dispersion in quite complicated geometries. When turbulence is present in the flow, the computation of particle dispersion becomes significantly more involved because of the random velocity fluctuations that preclude the deterministic computation of particle trajectories. One then may resort to stochastic computations of a great many trajectories with the aim to capture "average" particle dispersion. Models based on the Discrete Random Walk (DRW) have been used with success [3] to analyze particle transport in idealized inhomogeneous flows. A more general and promising approach is the so-called Continuous Random Walk (CRW) based on the non-dimensional Langevin equation [4]. This approach remedies most of the DRW shortcomings, e.g. the infinite fluid acceleration between discrete random steps.

The non-dimensional CRW model for particle dispersion has been recently validated in boundary layer turbulent channel flow [5] against point-particle Direct Numerical Simulation databases of Marchioli et al. [6] who produced detailed statistics of velocities and concentrations for particles having dimensionless relaxation times

* Corresponding author. Tel.: +41 56 310 27 11; fax: +41 56 310 21 99.
E-mail address: abdel.dehbi@psi.ch (A. Dehbi).

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doi:10.1016/j.powtec.2010.09.036

between 0.2 and 125. The CRW was shown to be in good agreement with the DNS data for the various measures of particle dispersion, e.g. evolution in time and space of particle concentration, velocity, and rms of velocity. The CRW model was additionally validated against empirical particle depositions correlations in mildly 3D flows, and found to give reasonable estimates of the particle deposition rates [7]. In this investigation, we aim at validating the model further in a challenging 3D configuration. We simulate henceforth mixing of two fluid streams in a T-Junction.

T-junctions are commonly found in a variety of applications which involve mixing of fluids of different properties. (e.g. in chemical or nuclear plants) and accurate knowledge of the mixing dynamics is highly safety relevant [8]. Owing to the complex turbulent nature of the flow, CFD investigations of T-junction mixing have focused in recent years on the use of Large Eddy Simulations (LES). Examples of recent LES studies of T-junctions can be found in [9,10] or [11]. Well resolved LES in principle captures most of the turbulent structures which govern turbulent mixing, and allows the determination of mixing dynamics parameters such as oscillation frequencies and amplitudes. In practice, mixing is obtained by simply solving for an additional scalar equation (e.g. temperature) in the framework of Reynolds Averaged Navier Stokes (RANS) or LES approaches. In this study however, we use Lagrangian tracer particle tracking instead to deduce the mixing. This effort therefore amounts to an additional validation of the Langevin CRW against 3D experimental data. Both the complicated flow in a T-junction and the tracking of small inertia-less particles render this a challenging test for the CRW model.

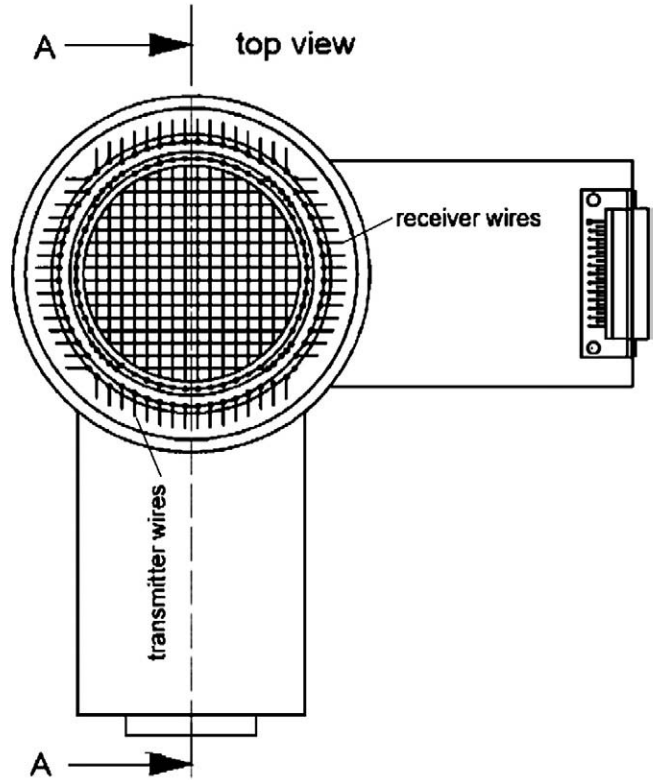

Fig. 2. Schematic of the wire mesh sensor (WMS).

2. Geometry and boundary conditions of the simulated experiments

The investigations reported in this paper aim at simulating isothermal T-junction mixing tests conducted recently at the Paul Scherrer Institute ([12,13]). The tests yielded a detailed database that is ideally suited for CFD code validation. The experimental set-up is shown in Fig. 1. The piping is made from Plexiglas with an inner diameter of 51 mm. The main and branch pipes have length of 1000 mm and 500 mm, respectively. Tap water flows in the main branch pipe, whereas de-ionized water flows in the branch pipe. The two water streams have very different electrical conductivities, which allows one to measure mixing with a specially designed wire mesh sensor (WMS) [14]. The WMS consists of 16 parallel transmitter wires and 16 parallel receiving wires, both having a pitch of 3 mm. The transmitting and receiving wires cross perpendicularly as shown in Fig. 2. Hence data are collected in 16 times 16 points of a given cross section. The WMS can be displaced in any plane downstream of the T-junction to collect mixing data as a function of distance. The data processed from the WMS signals allows the determination the instantaneous, mean and standard deviation of the "mixing scalar", which is proportional to the concentration of the main branch fluid. It has value of 1 for the high conductivity main branch fluid and 0 for the low conductivity side branch fluid.

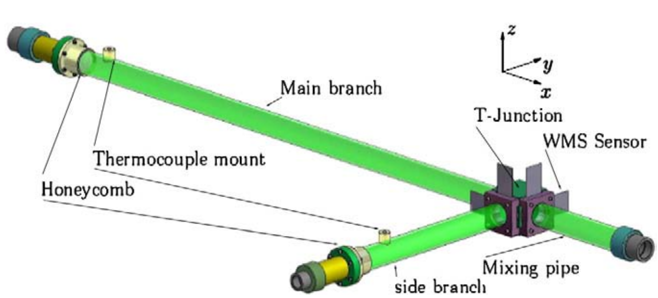

Fig. 1. Schematic of the T-junction test facility.

The measurement error of wire-mesh sensors was systematically determined by Rohde et al. [15]. These investigators found that the sensors behave linearly over a wide range of conductivities and that the average absolute errors in the mixing scalar are $\pm 3\%$ and $\pm 4\%$ of the mean value at the lower and upper end of the range, respectively. The WMS wires occupy about 3% of the flow area and hence slightly disturb the downstream flow, but they have no effect on the upstream flow or the local tracer measurements.

The experimental test matrix consists of a dozen tests with various combinations of flow rates. Only three, namely tests T1, T2, and T3 (see Table 1) are simulated in this investigation. These cover equal flow rates at high and low Reynolds numbers, as well as a case where the main flow is 2.5 times larger than the branch flow.

3. Stochastic Lagrangian tracking of tracer particles

Mixing in this investigation is determined via Lagrangian tracking of tracer particles which are injected at the inlet faces of the two branches and subsequently tracked. The inertia of the particles has to be small enough in order for them to faithfully follow the fluid flow but large enough to get a reasonable trajectory integration time step.

Table 1
Experimental conditions of the simulated tests.

Test	Main branch flow kg/s	Side branch flow kg/s	Mixing pipe Reynolds number
T1	0.5	0.5	44,000
T2	0.1	0.1	8800
T3	0.5	0.2	30,700