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Simulated time-dependent data to estimate uncertainty in fluid flow measurements

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ABSTRACT

Positron Emission Particle Tracking (PEPT) is an emerging measurement technique for Lagrangian data collection in experimental fluid flows. The nature of the measurement extends the study of turbulent flows to applications lacking optical access. A simulated pipe flow PEPT measurement is used in this work to verify reconstruction algorithm and identify novel sources of uncertainty. Simulated measurement occurs in a 38 mm diameter pipe with 0.55 m/s mean flow velocity and Reynolds number equal 21,000. Flow is simulated using computational fluid dynamics (CFD), generating 1000 time-dependent trajectories of tracers from CFD to prescribe movements of 40 µCi, fluorine-18-point sources. Geant4 Application for Tomographic Emission (GATE) simulates the response of the Inveon Pre-Clinical scanner model and produces an array of coincidence lines for the prescribed sources. The array is provided to a multiple PEPT (mPEPT) code reconstructing the position of simulated tracers and assigns positions to coherent trajectories. The mPEPT reconstructed trajectories are compared to prescribed positions. Reconstruction of 754 trajectories is achieved with measurement bias centered at 0.0 mm in all directions and standard deviation of 0.29 mm, 0.29 mm, and 0.30 mm in the x, y, and z component respectively using 2.0 ms time-steps. Two instances of position misassignments induced by the close-approach of two tracers in measurement volume are identified. This is a novel reconstruction error to PEPT measurements, unable to be identified without prior knowledge of tracer trajectories provided by these simulation tools.

1. Introduction

Isotopes decaying via b+ like fluorine-18 emit a positron, the antiparticle of the electron. When an electron and a positron collide, they produce twin 511 keV gamma rays. Conservation of energy and momentum results in the two rays traveling back-to-back, or at 180-degree angles with respect to each other. Shaw first described the line traced by these two rays as a Coincidence Line (CL) (Shaw, 1978). He established the idea that positron emitting isotopes could be bound to a tracer in flows of interest and tracked by clustering the CLs detected during a time-step. Moving tracers continuously emit CL along their trajectory. Parker and others named the method Positron Emission Particle Tracking (PEPT) and used the method to reconstruct the flow-field in a rotating drum (Parker et al., 1993). The PEPT technique has since been used to evaluate flow in milling equipment (Morrison et al., 2016), dishwashers (Perez-Mohedano et al., 2015), and hydrocyclones (Chang and Hoffman, 2015) as examples. More recently PEPT has been extended to allow tracking of multiple tracers without knowledge of initial tracer number or location (Yang et al., 2006). A multiple PEPT (mPEPT) method using adaptive clustering to independently find positions of sources each time-step before assigning the position to a coherent trajectory has been developed by researchers at the University of Tennessee (Wiggins et al., 2017). The ability to introduce tracers upstream of measurement is useful for applications where tracers pass in and out of the scanner's field of view (FOV), such as pipe flow where the measurement volume is limited to a section of the pipe.

In the future, PEPT may be used to investigate twisted tape inserts (TTI) which are found in a number of nuclear systems such as plasma facing components in fusion systems or coolant channels in the core of a fission reactor. TTIs enhance turbulent heat transfer, however the precise mechanism for how TTIs improve heat transfer is unknown (Clark, 2017). Previous authors have suggested TTIs may reduce the viscous sublayer thickness on the heated wall and induce swirl flow, increasing the mixing of fluids (Hata and Masuzaki, 2010). PEPT measurements could investigate this phenomenon by directly observing flow-following tracers in the near wall region. The reconstructed

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Nomenclature

$C_{\varepsilon 1}$	Turbulent kinetic energy dissipation rate constant 1, dimensionless
$C_{\varepsilon 2}$	Turbulent kinetic energy dissipation rate constant 2, dimensionless
C_{μ}	Eddy viscosity constant, dimensionless
d_p	Diameter of suspended particle, m
k	Turbulent kinetic energy, m^2/s^2
l	Length, m
r_p	Radius of suspended particle, m
Stk	Stokes number, dimensionless
u_o	Fluid velocity,m/s
u_t	Velocity of tracer, m/s
x_p	Prescribed x position, m
x_r	Reconstructed x position, m
y_p	Prescribed y position, m
y_r	Reconstructed y position, m
z_p	Prescribed z position, m
z_r	Reconstructed z position, m
μ_f	Dynamic viscosity, Pa−s
ρ_p	Suspended particle density, kg/m^3
σ_k	Turbulent kinetic energy constant, dimensionless
σ_{ε}	Turbulent kinetic energy dissipation rate constant, dimensionless

trajectories could be used to analyze the flow-field, however, the position uncertainty in such measurements may be too high to perceive changes in the viscous sublayer.

While PEPT measurement is well developed and becoming more widely used, the characterization of the uncertainty in a measured tracer trajectory remains incomplete. The current PEPT literature suggests the precision of the tracer location is proportional to the scanner's full width half maximum resolution and inversely proportional to the number of coincident lines used to locate the tracer taken to power one half (Bickell et al., 2012; Chang and Hoffman, 2015). In recent experiments, mPEPT has been validated using optical methods on a jet flow (Langford et al., 2016a). However, the optical measurement was not performed synchronous to the PEPT measurement, so only averaged and statistical comparisons of data could be performed. The need for performance assessments of time-dependent mPEPT measurement of tracer trajectories remains (see Table 1).

Prior works have also demonstrated degrading position resolution as two tracers approach closely (Wiggins, 2017). A reduction in resolution during close approach can lead to the confusion of one tracer for another in the assignment of positions to trajectories. This form of measurement error is common to optical tracking methods. To minimize the misassignments, trajectory linking approaches derived from optical tracking literature (Wiggins, 2017) are implemented in the mPEPT code. However, trajectory misassignment is difficult to detect in real flow measurements, as there are no positional data collected synchronously to the measurement. Extending PEPT and mPEPT to the measurement of Lagrangian turbulence requires trajectory misassignment and noise associated with the measurement to be reliably identified and separated from the actual flow induced movements of the radiotracer.

This paper introduces a simulation chain to compare prescribed tracer positions to trajectories produced by mPEPT, identifying position misassignments and other forms of trajectory corruption associated with mPEPT when locations of synthetic tracers are known.

The simulation chain starts with a computational fluid dynamic (CFD) simulation of pipe flow using COMSOL Multiphysics software. The CFD outcome is then used to generate tracer trajectories typical of those expected in a turbulent pipe flow. The position of each unique tracer in the simulation is exported to a data file with timestamps every 0.5 ms of physical time. The tracer trajectories are then recreated as point sources in a Geant4 Application for Tomographic Emission (GATE) simulation of the Positron Emission Tomographic (PET) scanner. The GATE simulation creates synthetic scanner CL data that is provided to the mPEPT code. The mPEPT code clusters the synthetically created CLs to calculate the tracer positions for each time-step, later assigning these positions to trajectories. The predicted tracer trajectories are compared to the prescribed trajectories derived from CFD simulation. This comparison extends uncertainty assessment in the mPEPT measurement to trajectories typical of tracers in a turbulent flow and adds information to the uncertainties previously examined for mPEPT (Wiggins, 2017).

This is the first use of GATE for tracking of multiple tracers using mPEPT or comparing prescribed trajectories from CFD to the mPEPT predicted trajectories. The basis for simulation is a prior mPEPT measurement using a steady water flow of 0.55 m/s average velocity in a pipe of 38 mm diameter. Tracers of activity near 40 μCi were circulated through the tube using a pumped flow loop following approaches previously reported (Langford et al., 2016b; Patel, 2017). A schematic of the pipe flow of Reynolds number 21,000 modeled in CFD, with measurement volume modeled in GATE, is offered with a photograph of a prior mPEPT experiment in Fig. 1. The PET scanner measurement volume extends from 0.6865 m to 0.8135 m downstream of the tube inlet used for the CFD simulations. This corresponds to the Inveon Pre Clinical PET scanner's FOV centered at 0.75 m.

2. Methods

2.1. Computational domain/meshing

A CFD model is built matching the geometry and flow conditions of a steady pipe flow. The model is generated in COMSOL Multiphysics V5.1 using the CFD module. The geometry of the pipe is 1.0 m long with diameter 38 mm (1.5 in.). A finite element method consisting of mixed second-order free tetrahedral and first-order prismatic elements is generated using the physics-based meshing, which is optimized for CFD. Physics-based meshing considers the nature of the physics governing the application, using more or less resolution where needed to numerically solve the solution faithfully. For example, pipe flow has higher flow property gradients such as velocity and shear stress in the near wall region. Higher spatial resolution in the mesh size is needed to faithfully solve the flow-field to a desired tolerance. Other regions of the pipe, where gradients are not as strong, the mesh size expands. In this model, free tetrahedral mesh elements decrease in size as they approach the prism boundary mesh as prescribed by COMSOL Multiphysics' CFD physics-based meshing. Meshing is applied via the user-selected Coarse, Normal, and Fine options. Relative meshing resolution is shown in Fig. 2.

Table 1
Mesh Properties.

Property	Coarse	Normal	Fine
# of Elems.	104,726	336,534	658,322
Min. Elem. Size (mm)	6.02	4.03	3.19
Refinement Factor	–	3.21	1.96
Min. Elem. Quality	0.022	0.038	0.025
Avg. Elem. Quality	0.563	0.619	0.6467