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Positron Emission Particle Tracking (PEPT) for Fluid Flow Measurements

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HIGHLIGHTS

- A new method for tracking multiple particles using positron emission particle tracking (PEPT) is introduced.
- PEPT measurement of flow in a rectangular channel is tested against PIV and PTV.
- Further work is identified to improve performance of PEPT for flow measurement.

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ABSTRACT

Positron emission particle tracking (PEPT) is used to study the behavior of flow in a rectangular test section. A multiple-particle tracking technique (multi-PEPT) is proposed and tested using a once-through flow system and a preclinical positron emission tomography (PET) scanner. This measurement is then compared to particle image velocimetry (PIV) and high-speed particle tracking velocimetry (PTV) studies of the same test section. Uncertainties in the established flow measurement methods used to validate the PEPT performance are quantified. Mean flow velocity are compared as measured by the three methods. Minor variations are exposed in the data comparisons, and uncertainty exists due to the statistical nature of our PEPT method. Nonetheless, multi-PEPT is shown to be capable as a means of examining characteristics of a complex flow regime.

1. Introduction

Positron emission particle tracking (PEPT) uses positron emission tomography (PET) technology to locate the position of a moving activated particle (Parker et al., 1993). The tracer is labeled using a positron-emitting isotope such as ^{18}F, ^{68}Ga, ^{11}C or ^{22}Na. The positron annihilates with an electron in the near vicinity of the tracer particle, emitting back-to-back, coincident gamma rays. By detecting these coincident gamma rays, one can draw a “line of response” (LOR) between the two detection locations. Each of these LORs will pass near the location of the tracer. Examination of many LOR allows the position of the particle to be found. A collection of LOR is depicted in Fig. 1 to illustrate this method of particle location.

PET scanners most often are an array of detectors arranged in a cylinder, creating a cylindrical volume in which coincident counts can be collected. Data for this article were collected in a Concord Microsystems P4 scanner (Tai et al., 2001), with measurement volume diameter 261 mm and axial extent 78 mm. This cylindrical volume is surrounded by 10,752 crystals, arranged in 32 circular rings. Each crystal is 2.2 mm by 2.2 mm in cross-section, 10 mm deep, assembled in modules of 8 by 8, connected to a position sensitive photomultiplier tube. There are 168 modules in the P4 scanner which are designed for imaging of rats, mice and primate heads in support of pre-clinical medical applications. The P4 will return 5.62 true coincident counts per second for each kBq of activity in the bore when the activity is located near the peak sensitivity, at the bore center.

The scanner collects coincident counts as a function of time as activated particles move inside the bore volume. The coincident counts are represented as words encoding the locations of the two gamma detections, allowing formation of an LOR. The count words are intermittently separated by time stamps, allowing the coincident count list to be divided into time intervals. LOR from each time interval are used to establish location of particles in the bore. The sequence of particle locations thus acquired from successive time intervals are used to develop the particle trajectories. Thus, by introducing neutrally buoyant, activated particles into a flow

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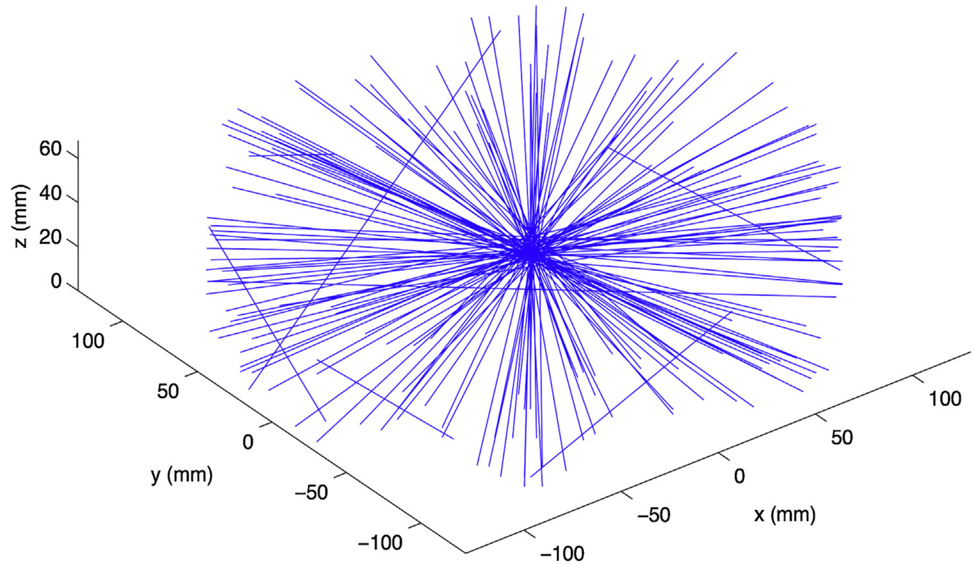

Fig. 1. Collection of 100 LOR from a point source in Concord Microsystems P4 Scanner.

regime, the PEPT method will measure a true four-dimensional (three spatial and one temporal) Lagrangian specification of the flow field. Furthermore, because this method uses the detection of 511 keV gamma rays, it is not limited to transparent fluids and apparatuses.

Since the invention of PEPT, it has been used to study a number of flow and industrial systems (Barigou, 2004; Chang and Hoffman, 2015; Chang et al., 2013; Griffiths et al., 2011; Parker et al., 2008; Volkwyn et al., 2011; Yang et al., 2014) with most studies being performed using a single activated particle. Further studies have been conducted using multiple tracer particles (Bickell et al., 2012; Yang et al., 2006), but these studies require a priori knowledge of particle number and initial location.

In this article we propose a new method for multiple positron emission particle tracking data processing, allowing a user to track multiple particles in a system with no need for a priori information regarding the number of particles or their initial positions. In this way, one can track particles entering and leaving the field of view of the system, as is common in fluid particle tracking studies. This method is then used to measure the trajectories of particles suspended in water flow in a narrow rectangular polycarbonate channel. After this, particle image velocimetry (PIV) and high-speed video particle tracking velocimetry (PTV) studies are conducted on the same test section for qualitative and quantitative comparison to our PEPT data.

2. PEPT Algorithm

The original and most prominent PEPT algorithm is that developed by Parker et al. (1993) at the University of Birmingham. The premise of this method (known as the "Birmingham method") is to collect a number of LORs collected between coincident crystal pairs and take the particle's position to be the point in space that minimizes the sum of the perpendicular distances from each of these lines. This method has been successful for tracking single tracers in many applications, and a slightly modified version has tracked up to three particles in a system where each particle had a very different activity (Yang et al., 2006).

Another approach was developed by Bickell et al. (2012) in which the scanner's field of view (FOV) is first segmented into a three-dimensional grid. LORs are then collected over a preset time slice, and the number of LOR crossings is counted for each point in the grid. Slices are then taken along the *x*, *y*, and *z*-directions at the point with the highest number of line crossings, and by applying a Gaussian fit in each direction, the particle's position and uncertainty can be found. A derivative of this "line density" method has also been used for tracking multiple particles, but in this case it is required that the user know the number of particles in the system and their initial positions before calculation.

2.1. A Novel Clustering Approach

We have created a new algorithm for multiple positron emission particle tracking that uses elements of the line density method but can track multiple particles without the need for a priori knowledge of the system. In our method, after creating the 3-D grid and counting the number of LOR crossings for a given time step, we use a modified version of *k*-means clustering (MacQueen, 1967) known as G-means (Hamerly and Elkan, 2003) to identify areas with larger numbers of line crossings. The centroids of these regions are taken to be the positions of the tracers.

The G-means algorithm is a divisive clustering tool based off the well-known *k*-means algorithm. In this method, one begins by performing a *k*-means clustering of the data set with $k = 1$. One then tests this cluster based on how normally distributed it is along its main principal component and decides whether or not to split the cluster. If the cluster fails the test, it is "split" and the data set is clustered with $k = 2$. Each of these clusters is then tested and subsequently split if necessary. This process continues until all clusters pass this test. The following is a brief discussion of this process. For a fuller description, see Wiggins et al. (2016).

The test is performed on a given cluster by first diagonalizing its covariance matrix to identify its main principal component and the corresponding eigenvalue, λ. One then initializes two daughter centroids along this axis, a distance $\pm(2\lambda/\pi)^{1/2}$ from the original centroid of the dataset and performs a $k = 2$ clustering of this data set using these as the initial centroids. A line is then traced between the centers of the two new clusters, and the data is projected along this line, reducing its dimensionality to one. A one-dimensional Anderson-Darling (A-D) test (Anderson and Darling, 1952) is then performed on this data. In this test, the A-D statistic is calculated for the set based on its normality, and if it falls below some predetermined critical value, the set passes the test. If a cluster passes this test, it is accepted. If it fails, it is rejected, and the two new