Study of Dynamic Geometry in Simulation and Reconstruction of Liquid-based Detector

Jingshu LI Shu ZHANG Zhengyun YOU

Sun Yat-Sen University

Introduction

Liquid-based detectors are widely used in particle and nuclear physics experiments. Fixed method is used to construct the geometry in detector simulations such as Geant4, it is usually difficult to describe the non-uniformity of the liquid in a detector. We propose a method based on geometry description markup language and a tessellated detector description to share the detector geometry information between computational fluid dynamics simulation software and detector simulation software. This method makes it possible to study the impact of a liquid flow and non-uniformity on the key performance of a liquid-based detector, such as the event vertex reconstruction resolution. This will also be helpful in the detector design and performance optimization.

Methodologies

A typical application of the method is in the experiment using optical photons to reconstruct event vertex and energy of the physical signals, in which the density and refractive index of the liquid medium may change in different parts of the detector due to changes in temperature and pressure. Consequently, transportation of the optical photons in the medium will also change and lead to deviations in detector simulation, event reconstruction, and detector performance.

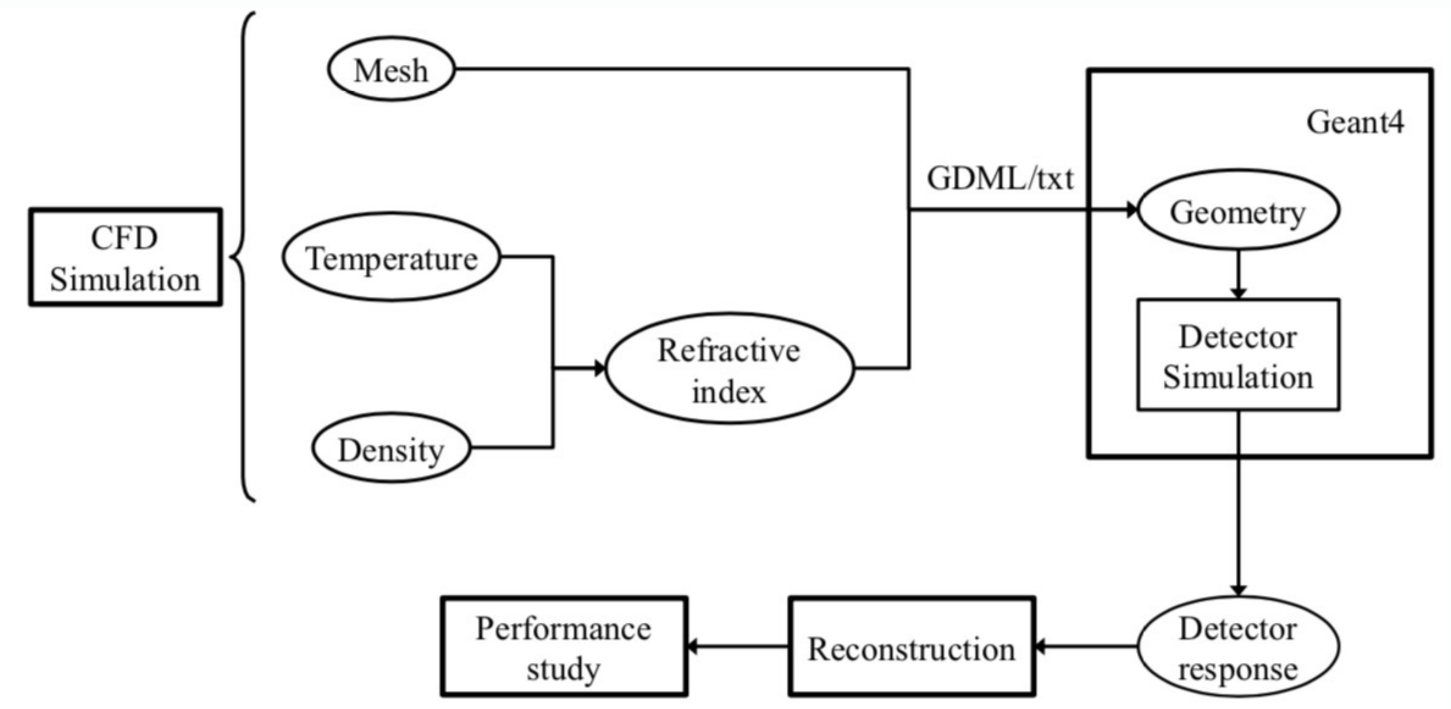

Fig. 1: Data flow of the detector geometry information from simulation to reconstruction

Application

We use a toy detector model to demonstrate the feasibility . A simple spherical volume filled with water is constructed as the detector. Assuming the temperature distribution is not uniform in the spherical detector, the density of the water will be different in the detector. To simulate a physics event at a fixed vertex inside the sphere, optical photons are generated from the vertex isotropically in the 4π solid angle. For the optical photons crossing the neighboring tessellated volumes with different refractive indexes, only the Fresnel refraction is processed.

A. Detector mesh geometry

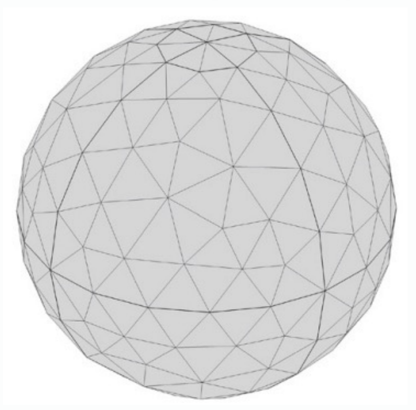

Fig. 2: Mesh geometry of the sphere

B. Fluid properties in CFD simulation

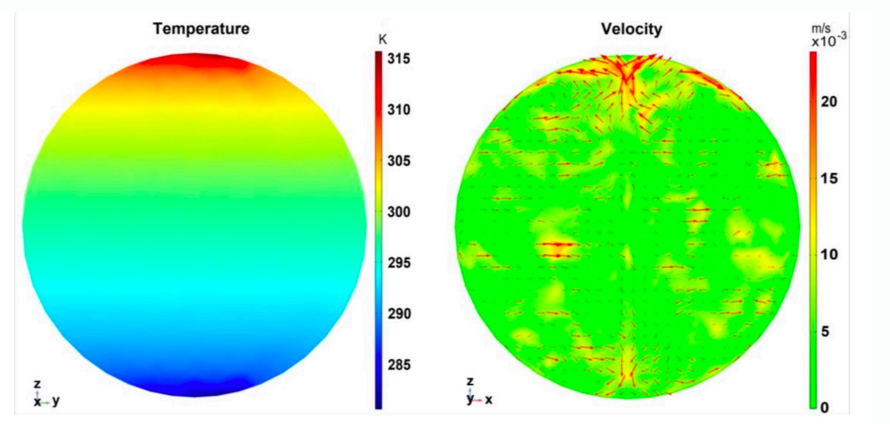

Fig. 3:Fluid temperature (left) and flow velocity (right) distribution in the spherical detector

In CFD simulation based on COMSOL, a fixed temperature difference is set between the top and bottom of the detector as boundary conditions. The temperature at the top is set to be higher than the temperature at the bottom. Constant heat flux is provided in the top and bottom areas to simulate the temperature difference from the environment.

C. Deviation in detector simulation

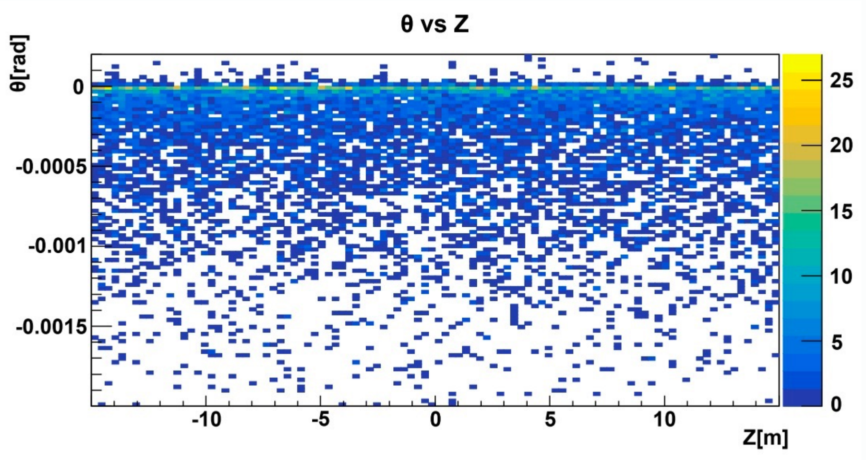

Fig. 4:Distribution of the deviation angle θ (top) with the Z-coordinate

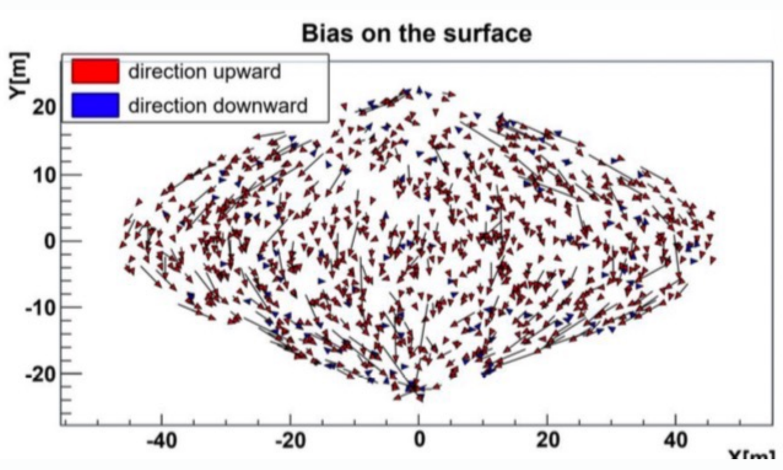

Fig. 5: A 2D projection of the magnitude of the offset on the sphere surface

We first simulate with the uniform medium detector to get the nominal simulation outputs. Then we run a second simulation with everything unchanged, except that the uniform sphere is replaced by the tessellated geometry describing non-uniform medium. Each event is simulated twice with the two different detector descriptions to get the deviation. Then we can compare the photon hit positions on the detector surface due to refraction caused by medium non-uniformity.

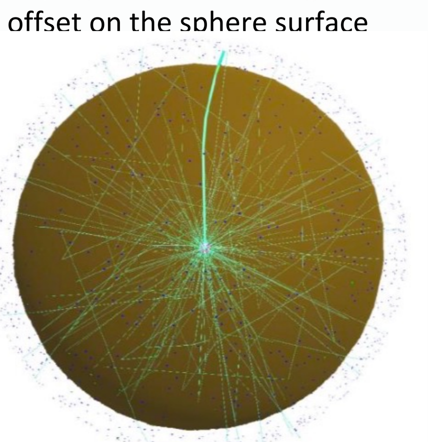

Fig. 6: Schematic of photon transportation in a spherical detector. The bold green line shows the path of a photon

Deviation in vertex reconstruction

Fig.7 shows the distribution of reconstructed vertex deviation for the 10,000 events. The average deviation is approximately 10 mm. The two simulation results are reconstructed with the same charge-weighted algorithm.

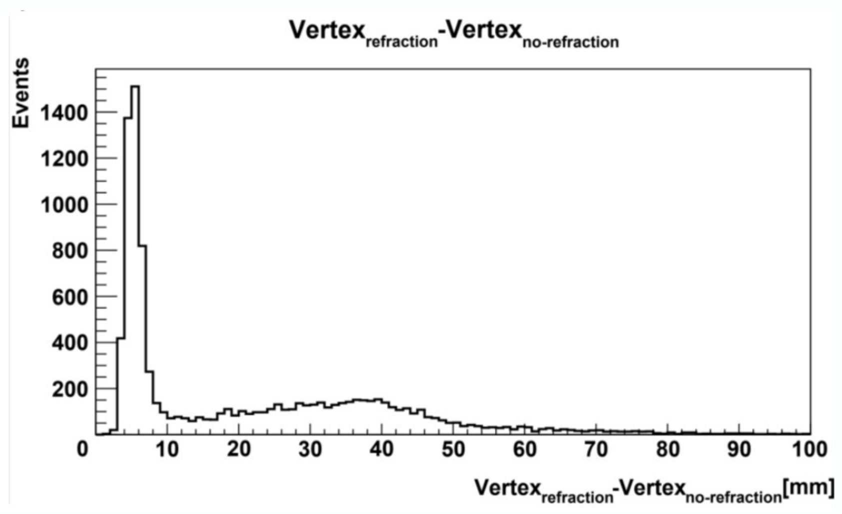

Fig. 7: The vertex reconstruction deviation owing to difference in geometry

Comparison

To study the influence of different conditional parameters on the detector performance, we change the size of the detector, the temperature difference, and the mesh granularity to check the consequential changes on simulation and vertex reconstruction results.

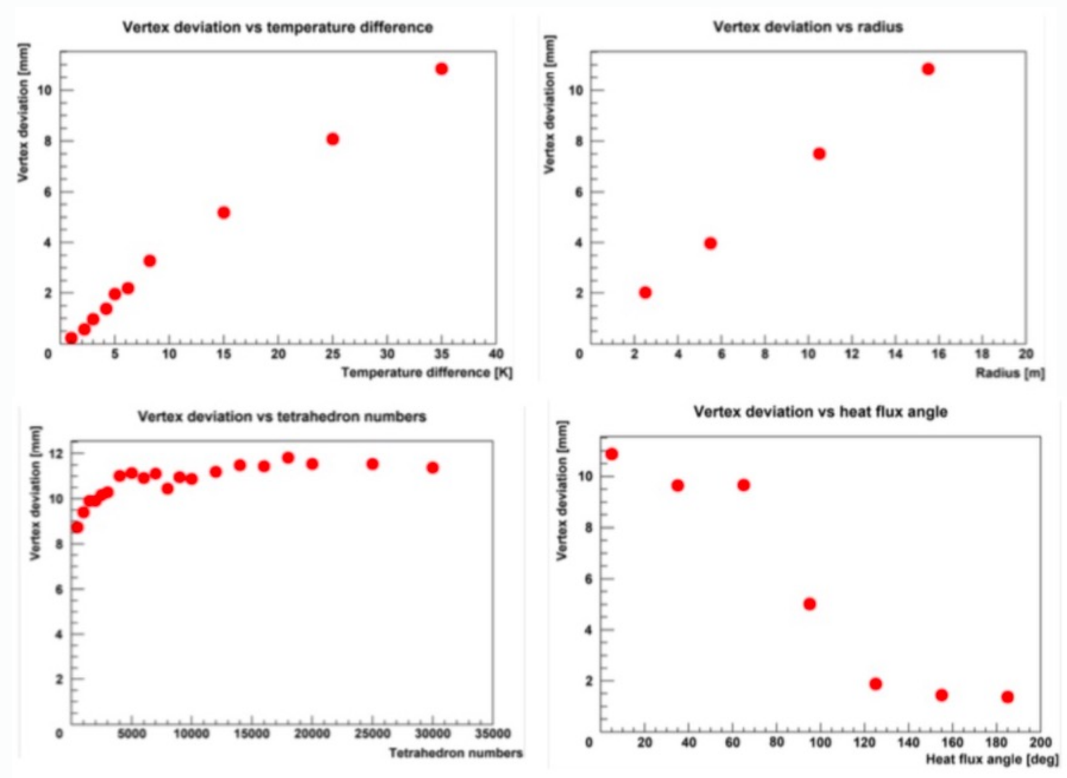

Fig. 8: The average deviation of the reconstructed vertex changes with the temperature difference, the radius of the sphere, the segmentation accuracy and the heat flux area angle.

Fig.9 shows the temperature distribution that reaches stable when the heat flux region deviates from the Z-axis by 30 degrees and by 150 degrees, respectively, in which the red and blue areas on the surface represent hot and cold areas where heat flux exists.

The simulation time with different numbers of tetrahedrons is listed in Table 1, which is the CPU time for COMSOL to simulate fluid flow for 5 hours clock time and for Geant4 to simulate 100,000 particles. The CPU time used by the two geometry data conversion methods of text format and GDML is also compared.

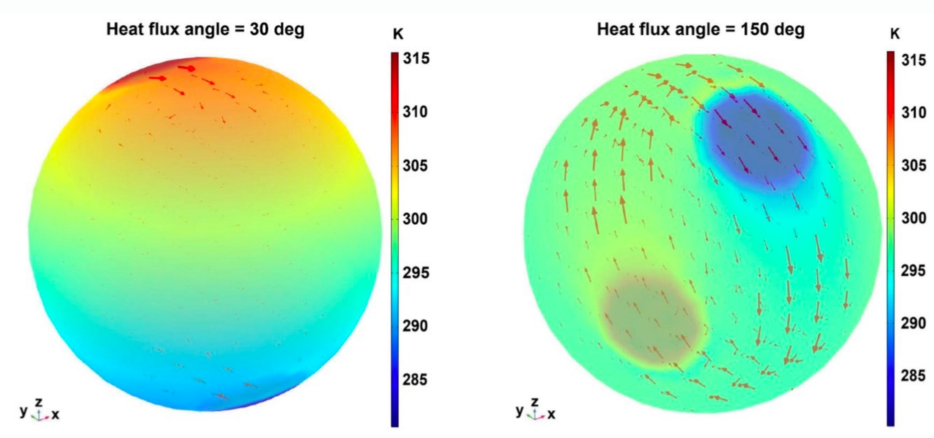

Fig.9 The distributions of temperature and liquid flow in the sphere when the CFD simulation reaches stable, for the two cases when the heat flux area deviates from the Z- axis by 30 degrees (left) and by 150 degrees (right), respectively

Tab 1: CPU time consumption for each part of the simulation

tetrahedron numbers	Geant4			COMSOL
	Geometry initialization		simulation	
	Text	GDML		
1,000	<1s	8s	27s	21min
10,000	2s	13s	58s	137min
30,000	7s	44s	85s	321min

Conclusion

A method of dynamic geometry information sharing between a CFD simulation and a detector simulation is proposed for liquid-based detectors. Its feasibility is demonstrated by applying the method to a simulation with a non-uniform medium to study the photon transport and a deviation in the event of a vertex reconstruction. This method can also be used to study other dynamic geometry-related problems in particle and nuclear physics experiments, such as the expansion and contraction of the detector volumes owing to a temperature change, detector alignment at different running periods of the experiments, and geometry-related changes to the magnetic field.

References

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Address: No. 135, Xingang Xi Road, Guangzhou, 510275, P.R. China

Email: lijsh53@mail2.sysu.edu.cn