Development of Multiple-Particle Positron Emission Particle Tracking for Flow Measurement Dr. Cody Wiggins, VCU, USA

Patricia Paviet
Good evening as well. It's a pleasure to have Dr. Cody Wiggins with us from the Virginia Commonwealth University, where he is currently employed as a postdoctoral research associate in the Department of Mechanical and Nuclear Engineering. He received his bachelor from the University of Tennessee, Knoxville in Nuclear Engineering, and his Ph.D. in Physics in 2019.

Dr. Wiggins research has focused on experimental fluid dynamics, including pure and applied research components. His primary interest has been in the development and deployment of Positron Emission Particle Tracking, PEPT, a radiotracer-based method for flow measurements in opaque systems. He is now studying thermal hydraulics for advanced energy applications, while maintaining a focus in the advancements of PEPT.

I would like also to acknowledge that Dr. Wiggins was the winner of the American Nuclear Society's Pitch your Ph.D. competition in November 2019. So, Cody, thank you again for volunteering to present this webinar. And I am giving you the floor. Thank you.

Cody Wiggins
All right. Thank you. Okay. Jumped a slide ahead there. Let's pop back. Anyway, thank you very much for that introduction. As they said, I'm Cody Wiggins from VCU, Virginia Commonwealth University. And today, I do want to talk about positron emission particle tracking, specifically some work I did during while completing my Ph.D. at University of Tennessee under Arthur Ruggles.

As Patricia also said, this was in the work I presented at last year's ANS winter meeting as part of the Pitch your Ph.D. competition. So, I'm very grateful for this opportunity to kind of expand that little three-minute talk out into a longer one to get to you all today.

As far as what I'll talk about today I want to give a motivation for why we are concerned about this specific flow measurement technique and then kind of break down what is PEPT or PEPT as I'll generally pronounce that acronym. I think I went to some of the multiple particle methods we developed at Tennessee and spent some time highlighting some of the various experiments we were able to conduct during my time at UT and then go over what's next, what's in store for PEPT including what we are doing now at VCU.

So, the real challenge to that, we are pursuing an answer for a solution for is flows in opaque systems, right? So, I mean these are ubiquitous, a number of engineering components. And specifically, if we look at reactor design, you have flows in heat exchangers all over the place in your reactor, in the secondary or even on the primary in some systems. Many of these – many Gen IV designs are really complex core geometry to be looking like packed beds or even just flow through rod bundles in you are making a traditional LWR design.

Challenge is how do you really understand what's going on at these really small scales and these complex geometries. And as we look at design and optimization of these components what we're often using are computational tools. So, we use Computational Fluid Dynamics, CFD, if we want to understand, say, flow inside a heat exchanger. You might then use something like – I'll show a COMSOL example on the bottom right there – some sort of computational tool to kind of model your system geometry, the flow inside it, and understand what's going on.

And this is wonderful, you get beautiful data, you can do a lot of really fantastic engineering work in this manner. But still a challenge persists that somewhere along the line you are going to want experimental data. So experimental data may be used directly to test a component, give you information on whatever it is you are wanting to install into your reactor.

The experiments may also be needed – I should say are needed for a validation of simulations. Anytime you have this computational modeling going on, it's important to make sure you are properly recreating reality. And in many of these geometries, getting that experimental data can be quite difficult.

And so, I'm talking about opaque systems specifically because many of our traditional kind of high-resolution experimental fluid dynamics techniques rely on optical access. So, you are using something like cameras and lasers to illuminate – they are using lasers to illuminate the flow field and then cameras to track seated particles or something in order to understand the underlying fluid dynamics as it becomes very difficult if you are using metallic components or something of that nature.

So, you are often left using some sort of surrogate fluids or surrogate materials, representative geometries, things of this nature to allow optical access. And if you want to work in these opaque systems, you often have to use – you can use other experimental techniques, things like ultrasonic techniques, UVP, MRI-based techniques but these all come with their own limitations.

UVP’s not super high resolution. If you want to use MRI, you can't work in metallic system to reduce [ph] currents. I’d say there are still these outstanding challenges in understanding flow and components of this nature, which brings us to PEPT. So, Positron Emission Particle Tracking, that's the name of the game or PEPT as again I'm going to call it.

And as I said previously, one of the common ways to understand flows experimentally is essentially add in some sort of neutrally buoyant tracer particles to your flow system and you track those particles. And by tracking the particles, you can understand the underlying flow field. So that's effectively what PEPT is doing but instead of doing it with lasers and cameras, we are going to do it with a PET scanner, so it's Positron Emission Tomography, the kind of thing the doctors might use to look inside of you. So again, we are kind of adapting medical imaging technology to do flow measurements in opaque systems.

And what this is all based on, it's you're going to be using detection of relatively high energy gamma rays 511 keV to do this imaging, so you can look through things like, say, I show examples on the right. So, understand, you can look at flow in a dishwasher. You can look at flow in some sort of commercial heat exchanger.

You're not restricted to having to use transparent materials. Again, the data that you get from PEPT or what we call Lagrangian data, meaning, we're actually tracking individual particles moving along over time and that kind of gives us some unique information as opposed to things we are more or less capturing, snapshots of a flow field.

And then this is a kind of natively 3D technique, which gives us, again, some interesting data. And presently the technology, and I'll get into this a little bit later, allows for resolutions on the order of hundreds of microns reconstructions at every millisecond or so, so about a kilohertz reconstruction frequency.

That's all well and good on like kind of what is PEPT. Now, as far as how it works, the general process of this whole technique is you are going to take some positron emitting radioisotope. So, I gave some examples of common radioisotopes used here at the bottom left and you'll attach that to again a neutrally buoyant tracer particle. You'll introduce that tracer then into your flowing system.

As that tracer then moves along throughout your – whatever the equipment you are studying is, positrons will be emitted by a radioisotope and they will annihilate with electrons in the near vicinity of your tracer particle. So, right, they'll come off. They'll find an electron pretty quickly and annihilate. That annihilation event will create back-to-back coincident 511 keV gamma rays.

And so, what you'll do is you'll take whatever your system of interest is and you'll put it in the midst of some detector array. Typically, again, we use a PET scanner. And by detecting all these coincident events, you can then kind of subdivide all your events into time steps and begin to build trajectories of these individual flow tracers as they move through some system of interest. So, this data set I am showing on the bottom right from Chang and Hoffmann, this is flow in a hydrocyclone separator for instance.

Now that last bit of how do I go from detection events on a scanner to physical trajectories of a particle is very non-trivial. If you think about what these raw data look like, again it's all these coincidence section events segregated by time, but how we typically like to represent those is lines. So, we call them coincidence lines drawn between those coincident detection sites.

And in a given time-step what that big cluster of lines may look like is something like this on the left. So again, the question is how do I then take this and triangulate the position of a tracer at a given time step?

Well, there's been a lot of ways people have done this in the history of PEPT. So, the oldest and most prominent PEPT group in the world is university of Birmingham in the UK. And they use a simple yet very elegant method to do this PEPT reconstruction.

And I would say this Birmingham method is by far the most commonly used method for PEPT reconstruction. And it's simply you are minimizing – you are finding the point and space that minimizes the sum of squared distance to all of the lines, right. So, this is like what you may do in data analysis where you'd fit a bunch of points to a line. You are just doing it backwards. You're fitting lines to a point and then they use some different iterative methods to reject noise and find the tracer's particle in each time step in this manner.

A couple of other methods that have been used are from University of Bergen. This is a Norwegian group at Bergen and then Cape Town out of South Africa. And the reason I want to highlight these methods is they both rely on kind of segmenting the field of view of your pet scanner, your detector array into pixels so to speak.

So, what the Bergen method does is they take all of the lines in a given time step, project them onto a 2D plane and then trace lines onto a 2D grid kind of pixel grid and by finding the maximum line crossing pixel, they say, okay, that's where the particle is in this 2D plane. Then they do the same thing in an orthogonal plane to isolate the particle. And then I guess the third component of its position. The Cape Town method does something very similar. But instead of doing this in a 2D plane, they segment the entire field of view into 3D grids or what we refer to as voxels, volumetric pixels, and they find the voxel with the highest number of line crossings and call that the position of a tracer.

So, what we want to do as we kind of advance PEPT as a method and kind of we are after Tennessee is multiple particle tracking. So, all these methods I've described previously are mostly used for tracking a single particle at a time, so you only have one particle in the field of view of your scanner and then many of them had kind of multiparticle variants but with limitations.

So, the Birmingham method has been used to track up to three particles simultaneously, but it required that you knew how many particles were in the field of view of the scanner. It also required the tracers to be a very different activity. So, you needed to have one of say like one millicurie, two millicurie and four millicurie. And you start to run into some issues in setting up experiment in that manner.

The Bergen method's only been used for single particle tracking to my knowledge and the Cape Town method has been used to track up to 16 tracers. So, it was an excellent mark to hit. However, it required that you knew how many tracers were in the system and it also required you knew the initial positions of your tracers in order to do the triangulation of their final locations.

But what we are wanting to do is find a method that doesn't have these restrictions. What we want is something that allows tracking of an arbitrary number of tracers. You don't need to tell it – you don't need to give the algorithm priority [ph] information on number of particles in the system and something that allows tracers to go in and out of the field of view of your scanner.

The reason we want this second capability is to be able to create a kind of a flow loop-based system where particles can enter and exit a test section, a region of interest in a component so that we can build long-term time average statistics of the flow field.

And that kind of brings us to where we are at or where we were at, at University of Tennessee. This was all work done under Dr. Art Ruggles in the Nuclear Engineering Department. I show some images of our group and our lab facility here. And so, we were working under the NNSA’s radiochemistry center of excellence at the University of Tennessee, working to develop these multiple particle PEPT techniques for understanding flow in various complex systems. And again, with kind of our initial focus being on how do we come up with new more robust reconstruction algorithms that allow multiple particle tracking with again arbitrary number of tracers.

So, this is what we came up with and we call this the feature point identification method. That name is taken from some optical particle tracking methods. And so, what you'll see is what we wound up doing is kind of adopting techniques from the optical particle tracking world into PEPT. So again, you start with this raw dataset that is a bunch of lines, so a snapshot of hundreds or thousands of lines.

And this specific data that I am showing is for three particles. So, for this experiment there are three particles near the center of the field of view of a scanner. So again, the question is how do I isolate them? And when you just look at this cluster of lines, it can be difficult to say that there are three there. But if we start again as the Cape Town method did and say, okay, let's trace all these onto 3D voxels, it starts to become apparent that there are three regions of what we call high line density.

So, you can see after doing this line density tracing, clearly three particles appear to be present. Now the question is how do we get a computer to recognize that so we can do all this automatically. And what we recognize at this point is what we've effectively built is a 3D image. So, this is very similar to how PETs, the tomographic reconstructions work. And this line tracing is what they would refer to as a back projection.

But by recognizing that what we have now looks a lot like a grayscale image. Just in 3D, we can apply optical particle tracking techniques. So, right, these are all voxels with the scalar value, representing the number of line crossings. Again, that's very similar to pixels with grayscale values. So, we can apply something like a simple smoothing filter to kind of cut out any long wavelength noise in the image. And now it starts to become even more apparent where those regions of high line density are.

So, we can do a sort of local maxima search throughout this whole scanner field of view to find again these voxels that are local maxima in the line density grid and then use Gaussian fitting to get sub-voxel accuracy here. So, we can find fairly precisely where the final position of the particles are down to about one-tenth of an individual voxel size.

So, with this method, you then have all of these individual time steps, where you know the locations of individual tracers and you can, again borrowing from optical particle tracking, just do some – use the physics of the system to kind of project where your tracers are going to be in subsequent time steps and recreate continuous trajectories. You build these continuous trajectories of position histories of these individual tracers.

Yes. So, with this method in hand, we are able to set out and do kind of some different things. Again, we are getting that spatial resolution, temporal resolution, like I said at the beginning, order of hundreds of microns every millisecond. And I call this a typical performance because it can vary a lot depending on a number of factors.

One, the probably the biggest one is the activity of your tracer. If you are using a tracer of very high activity, you can do reconstructions much more quickly and with much higher accuracy; however, with lower activity tracers that performance diminishes. Also, if you are using a medium with a lot of attenuation present, you won't be able to get as many unscattered events or you'll have scattering present, which will kind of blur the image out so to speak, which can also affect resolution.

So again, we were after a multiple particle tracking technique and we've successfully demonstrated tracking of over 80 tracers simultaneously in experiments, so that's well ahead of what had been achieved previously. And in simulation data, we are showing capability to track more than that over up to 100. But now the question is how do we go from the simulation world to the experimental world, still some of the kinks to work out there.

And there's been another, in my opinion, interesting new experience we've been able to conduct with PEPT. So, I've kind of looked under the hood for a moment, if you will. We talked a little bit about how does the reconstruction work. So now to give you guys kind of a picture of what an actual PEPT experiment looks like, you really divide the experiment into two phases. So, there's an activation phase and a kind of flow experiment phase because again what we are doing is we have to create these radioactive tracers to then insert into our flow loop. There's generally two ways that people go about the activation phase. One is what is referred to as direct activation. So, this is where you take whatever your tracer particle is and you put it in a cyclotron or an accelerator of some sort and by bombarding it with protons or helium depending on the setup, you create the positron emitting radioisotope volumetrically within your tracer.

The other method for activation. This is what we actually use, is what we refer to as indirect activation. So, this is where you are actually using some chemical means to attach radiotracer onto the surface of your particle. So, this is why I guess we were working under a radio chemistry center is to employ the expertise of some radiochemists and how do we attach these radiotracers onto small particles.

So typically, what we were using as our tracer particles are anion exchange resin beads. These are hydroxide form resins. We use them of varying sizes from kind of, I guess, it was about 100 microns up to a millimeter in diameter. And depending on that size by soaking them in an aqueous solution of F-18, we could achieve activities per particle on the order of 50 microcuries up to a millicurie.

So again, I guess I said it briefly there. The tracer of interest for us was fluorine 18. So, we would have this in an aqueous ionic solution. And just again, we soak the particles in this solution, followed by kind of a rinsing and drying period, and then isolate the particles and add them to our flow loop.

The reason we use F-18, well, one, it's we had a definite chemical means of attaching it to our tracers but also this half-life of F-18 makes it very good for these experiments. You see the half-life is about two hours, 110 minutes. And when you're doing these experiments, and this is true a PEPT as well, it can be nice to have that kind of intermediate half-life, so you have a long enough lived isotope that you can get sufficient data collection but it's not so long-lived that it creates kind of a radiation safety problem.

So, when you are conducting these experiments, you can do your experiment, shut down your facility, lock the door and come back in a couple days. And at that point, this isotope will have decayed to background levels and makes for very easy cleanup.

As far as those experiments go, you require both a tracer and you require a detector array. And really what you need is some sort of segmented detector array. That's really the big necessities, you need position sensitive detection capabilities. And PET scanners provide that very nicely. So, PET scanner typically consists of some ring of these tiny segmented detector blocks, where you have – again, this kind of segmented detector face connected to a position sensitive photomultiplier.

These kinds of cylindrical geometry pet scanners are very nice and that they offer very high sensitivity as well as it makes your experiments very easily repeatable. There are some calibration challenges in PEPT that are unique to our technique. They're different than what you may encounter in PET.

So, having this kind of fixed gantry allows you to do a single kind of calibration routine and then you can easily de-warp all of your images, your trajectories and apply that for every experiment conducted. Other geometries that are commonly employed in PEPT. So again, I showed earlier that this dishwasher experiment that was done by the group at University of Birmingham. And they were actually using in this these kind of panel detectors and the Birmingham group has also used referred to as a modular detector array where they have taken individual detector elements, separated them out, and can position them however they like for getting an experiment.

And so, this setup is nice – either of these setups are nice and they give you a little more flexibility on the geometries you can examine. And again, there's kind of a trade-off on doing it one way or the other. So, what we were always using at University of Tennessee was a Siemens Inveon PET scanner. So, this is a pre-clinical PET scanner, meaning it's designed for animal imaging. And it consists of – so it's a small bore, it's not something that a human could fit inside of the field of view of this scanner.

I think there's a cylinder that's roughly I guess 10 centimeters in diameter and 12 centimeters long. And what's nice about this small-bore scanner is that tiny bore actually gives you a very good solid angle coverage for your detector array. And that was to achieve by PET standards very high sensitivity at the center of the field of view.

The scanner also gives very good time resolution, so we could do PEPT reconstructions up to 5 kilohertz depending on the needs of a given experiment. Now, these experiments typically consisted of a flow loop type setup. Again, that was one of the advantages of our multiple particle tracking method is it allowed this type of experimental design which is to have pump driven flow of, in our case, typically deionized water into a test section where the test section is placed in the center field of view of the PET scanner. So, you can see a photo of what that would look like on the left.

We are almost always using deionized water as our working fluid. And the reason for that is that since we were using a radiochemical means of doing this tracer attachment, you run into issues if you have too many free ions floating around in your working fluid. It doesn't ruin an experiment, but you can have much longer experimental data collection times if you are kind of ion free in your working fluid.

Now, again, the test section is placed into the center of the bore of this PET scanner. And you can kind of see by showing a couple images there. Some of the advantages of PEPT is you don't have to worry about optical access. And that can mean maybe your test section itself has something restricting visibility. It can also mean that maybe the support structures would have gotten in the way of a camera system. So, I showed kind of on this panel, this was an experiment where we had problems with vibrations. So, we could just simply add some foam padding and strap it down and that doesn't create any sort of interference with the measurement.

Don’t have to worry about that in the least. And then I guess lastly on these experiments, I will remind this is a radioactive material works, all this needs to be done behind shielding and with proper administrative controls to make sure you are away from the facility for ample amounts of time during data collection.

Now getting into some of the specific experiments we conducted, I do want to take some time and I guess do a little a little highlight reel of our experiments we did at Tennessee. Many of these are kind of demonstrating the capabilities of PEPT, as well as the capabilities of our reconstruction method. And then highlighting some of the future paths that we can take with PEPT.

So, as we began this journey, so to speak, of what can we do with PEPT, the first thing we wanted to know was say, well, can we image in a stainless-steel component? So here, I am showing actually the same heat exchanger I had a picture of on slide two or three. And so, what we were curious is how well can we resolve flow on the shell side of this heat exchanger around kind of this complex tube structure that's on the inside of a given heat exchanger as well as imaging through. I believe it’s about a quarter inch thick stainless steel in this case. And we were working at just barely turbulent Reynolds number conditions. So, it's about half meter per second flow.

And so, if I show here. What we can see is in short it was a success. We are able to see the flow of these tracers kind of curving around the structural baffles on the shell side, progressing through this heat exchanger. What I've got here are all the individual tracers have been colored by instantaneous velocity. So, one nice thing in PEPT, since you said you have these continuous – these time histories of tracer positions, you can apply some pretty simple – either via curve fitting or via convolution you can take the derivatives of these tracers and get things like instantaneous velocity and acceleration. So, we can see here how the flow kind of accelerates as it comes around the baffles, speeds up, slows back down and speeds up again as it passes the next set of baffles. We can see very fine flow features. It's a little hard to see them from this perspective. We can kind of see the little zigzags, the wiggles in the tracers and that's actually seeing how the flow moves around that complex tube structure. So, we are able to resolve a lot of these fine details even through quarter inch stainless steel.

Our next question came to mind was, okay, well, can we attempt to validate this, again, in a somewhat complicated flow structure. They are validated against a more conventional optical particle tracking method. So, with that in mind, one of my colleague Seth Langford devised this flow channel in which we have kind of a more or less 2D flow. So, this is a channel flow geometry with these baffles inserted and that those baffles are going to create kind of a recirculation region between the baffles, leading out into this jet flow structure back out into the free stream.

And this is all done within an acrylic test section, so we can then using optical means compare our PEPT results optical PTV results. So, if we look at what we reconstruct with PEPT, again, I show on the left these complicated trajectories reconstructed with PEPT, where you see, yes, this wild recirculation here, things speeding up between the baffles, and then the small recirculation region downstream going back out into the main channel flow.

So, we see that PEPT is able to reconstruct all these trajectories with effectively no issue. One of the interesting things that we came across in this experiment, there was actually the way this test section was constructed, a very small gap between the channel and the O-ring that was acting as a sealant. So, you could see some tracers every now and then skip around the baffles. Nothing too much concern but kind of interesting finding this experiment because I am showing here on the top right, these are all the same trajectories measured with PEPT, but we've got it overlaid with the geometry and showing each color represents a different tracer as determined by PEPT. That's what all these lines flowing through the test section are showing.

And we did the same experiment then with optical Particle Tracking Velocimetry, PTV, and averaged all these velocity data onto a 2D grid across the field of view to understand the time average mean flow in this system. So, I'm showing on the bottom right a comparison of PEPT and PTV mean flow fields measured and you see that they've matched very well even down to how the mean flow seems to turn slightly to the right at the end of the test section. So, we believe just some small effect of a slight asymmetry in our baffle setup.

Moving on to another experiment that we did to understand the performance of our PEPT technique. We then wanted to look at pipe flow. And the reason we were after pipe flow is this system is very well understood. There's a lot of good data to compare against for turbulent pipe flow and we selected this Reynolds number of 42,000 because there's existing DNS or Direct Numerical Simulation data at that comparable Reynolds number.

This was actually the experiment I mentioned – I touched on briefly that there are some PEPT specific – this is some PEPT specific calibration that needs to be done as far as de-warping – to correct some artifacts caused by scanner geometry, this was actually the experiment that really highlighted that.

So, without getting in too much detail, essentially there are some issues that arise if you do imaging too close to the radial edge of the field of view of the scanner. So, in this experiment, we were looking at roughly a three-inch pipe, which pushed out to near the edge of our scanner bore. This was actually the experiment where we came up with our calibration procedure to correct for this.

And again, in this experiment what we wanted to do is see how well do kind of time average statistics measured via PEPT match to what's been seen by other researchers and our comparisons are done against DNS data. So, for those not familiar DNS or Direct Numerical Simulation, this is computational data, but this is done without any modeling assumptions. So, this can often, if properly done, be considered the gold standard against which to compare your results.

And the datasets that we compare against had all themselves been validated against experimental data. And so, I am showing – I'll start here on the left. This is the mean velocity normalized into wall units, measured via PEPT. And I write this in again wall units, so this Y plus metric is measuring distance away from the wall.

So here, this would be the wall of the pipe and then this would be the center line. And what we can see is that our data, which are the symbols, this is time averaged mean velocity, match very well with the DNS data. Except for in the very near wall region you can see that we aren't quite able to resolve how the flow of mean velocity goes to zero at the wall.

If we then want to consider some higher order velocity data, this is something could be of a lot more interest when it comes to validation for turbulence models and CFD. And we can look at things like Reynolds stress and the turbulent kinetic energy budget. And again, we kind of [Unclear] that we generally match well to what's been predicted by the DNS data with the exception being in the axial Reynolds stress. So, the Reynolds stress is the second order – I guess you call it the second order moment of velocity.

We can see that again, we kind of get off in the very near wall region. One of the really neat capabilities of PEPT is that we are going to call this Lagrangian or particle tracking data, is that we can also understand things like instantaneous acceleration as well as look at kind of the displacement of particles over time to understand things like diffusion and material transport.

So, in looking at that, as shown on the left, the acceleration profiles we measured with again in comparison to DNS, and we see a very good agreement between our measurements in the DNS data in each of the three directions of interest. The other thing that's was kind of interesting is looking at the fourth moment of acceleration of the kurtosis. What we see is that all throughout the profile of this tube, we have distinctly non-Gaussian acceleration profiles. So, we are more intermittent – we have broader tails and a Gaussian distribution when looking at our acceleration distributions.

And this is fairly well-known to be – this is known to be the case in turbulent flow but it's interesting that we are able to measure that with PEPT, again a fairly novel technique in imaging opaque systems.

And the other thing I mentioned of interest is looking at things like mean square displacement, which is kind of a single particle metric of diffusion, and we can start to understand like how does transport get affected at the center line of the pipe versus at the wall.

Another experiment we did, and so this is starting to move away from just checking what can we do with PEPT to actually using PEPT for different validation and measurements is we looked at twisted tape swirl flow. So, this is pipe flow again, but we've added this stainless-steel twisted tape insert. And these inserts, they swirl the flow and that swirling motion kind of induces some secondary flows and enhances mixing, ultimately leads to improved heat transfer.

And so, we started looking at these because some colleagues of ours at Oak Ridge National Lab saw that some simulations were pointing to some interesting secondary flows that appear in these systems. So, what we are able to do with PEPT is make these measurements of the raw trajectories and then actually do a little geometric transformation to look at what's actually going on that rotating frame and then via time averaging in the rotating frame start to understand velocity profiles in this system.

So, one of the first things to look at is the mean axial flow. And this again is understood – it was predicted by the simulations shows kind of this asymmetric behavior where the peak axial velocity is not kind of at the center line of each of these semicircular channels. It's pushed off to the side by the swirling motion. But the other thing of interest, these were the secondary flows identified in simulation and it's that you have these kind of helical vortices that roll up within each channel.

And these continue to evolve even pretty far downstream of the splits. You can see how these secondary flows are changing from 20 diameters downstream of the start of the tape to 30 diameter. So, it's kind of continually evolving. And these are something of interest physically because between these recirculation regions, you can get kind of stagnation at the wall, which could lead to local hot spots.

This is kind of an interesting measurement we can take forward to better understand these systems for heat exchanger design. Now kind of the last engineering system of measurement that we looked at was pebble bed geometry, so this has obvious applications and pebble bed reactor design. And specifically, what we were looking at here was very low Reynolds number flow, the reason being we wanted to understand how the packed bed geometries themselves influence things like core scale velocity acceleration, diffusion, things of that ilk and be able to separate it from the effects of turbulence.

And so again, we saw that PEPT was very capable of imaging in a system like this even with all of the obstructions caused by these glass spheres. And this was the system that I hinted toward previously, we were able to track over 80 particles moving simultaneously in the system. As far as some of the kind of interesting quantities we were able to look at, looked at the core scale velocity and acceleration distribution. And again, see that we are non-Gaussian. What's interesting here is that's not being caused by turbulence, that's being caused by the geometry of the pore structures created in these packed bed geometries.

And then kind of getting to these diffusion type measurements, we can start to understand the scaling behavior of the mean square displacement. So, understanding how these tracers spread out over time, which gives us an idea of things like transport in the system. So, there's applications of that looking at in many pebble bed reactors what's the – how do fission products get from point A to point B within the reactor core.

And then lastly, I'll touch on a couple of biological applications. So, this is an engineering talk, so I won't dwell here too long. But looking at flows and opaque systems, that's not just restricted to the engineering world. There are definite things of interest to biologists as well. So, one of the systems we looked at was pulsatile flow in elastic tubing. So, this was done to simulate blood flow both on the top, this is in kind of an open geometry. And on the bottom, we actually just pinched this with a spring clamp because again these obstructions don't matter that much to PEPT, but we pinch this with a spring clamp to simulate stenosis or a blockage in your artery. And we were able to with PEPT resolve this acceleration and deceleration of the flow with the pulsing motion as well as things like recirculation downstream of the blockage.

And then a last kind of in my opinion quite interesting application of PEPT is looking at tracking of individual radio labeled yeast cells, so actually taking individual cells, labeling them with radiotracer and following them moving around in the system. And this has engineering applications looking at tracking the propagation of infection or inflammation within a body.

Now as I think about where's PEPT going next, there's obviously advancements to be made in the technique. And a lot of my time has been spent – I talked about this a good bit at the front of this talk – on the reconstruction front. So how do we get better and better reconstruction methods that can handle more tracers, have better spatial temporal resolution, things of that nature.

And one of the reasons I'm excited about kind of what we're doing or what I've been doing at Tennessee and now VCU moving forward is since I am using a method that borrows from optical particle tracking, we can keep doing that. So as people keep making advances in the PTV front, the particle tracking velocimetry front, continue to advance PEPT in that manner using these voxel-based techniques, people are not – and not everyone is doing things the same way.

So, if I look at what the University of Birmingham is doing right now. They've put out recently a very interesting algorithm in which they are essentially taking the midpoints between all of the lines in one of those represented data sets and clustering those midpoints to find tracers in each time steps.

So, using this clustering base technique they've been able to show in a simulation that they can track up to 128 tracers simultaneously. I mean this is an awesome breakthrough and I am very excited to see where this goes, especially as they start employing it for experiments.

Now if we think about kind of what are the technological advances that need to be made for PEPT to keep getting better and better, it mostly comes down to two things and it's better tracers and better detectors. So, with tracers, again, I think I referenced that you want to have high activity. So, the more activity you can have on an individual tracer, the more signal you get, and that’s the better resolution and detection.

The problem is how do you make a smaller tracer, so something that better and better follows the flow of your given geometry while maintaining that high activity. So, it's a challenge that we were looking at moving forward. And as I note here, that may require looking at different radio isotopes, different radio labeling methods.

And then the other thing you want to maintain in all of these – for all these tracers is some sort of the mechanical toughness as I call it. We don't want something that's going to just break apart when you add it into a flow system, especially if we want to start looking at things like liquid metal flow or molten salt flows where you have high temperatures to take into account.

And as far as detectors, I love our setup with the Siemens Inveon with this small-bore cylindrical pet scanner. But there is something to be said for the folks doing with a more modular design. It really allows you to incorporate more interesting geometries into your experiments and then really just kind of the generic better detectors improves PET resolution or PEPT resolution.

And so, what I mean by that is that as PET is advancing as a field, we are getting new detectors with smaller crystals and better electronics and things that allow time of flight and better timing. And all these things will then show subsequent improvements to PEPT if we can get our hands on these newer PET scanners. Because the big thing caused by these finite sized crystals within each detector do create some interesting geometric artifacts in the reconstructions. So, as you get smaller and smaller crystals and better detectors, you can lift some of these artifacts and improve resolution.

Now, I hope that thus far in this presentation I've at least in some way swayed you that PEPT is useful for a number of flow measurements in some interesting geometries. The question is then how do you deploy this for yourself. And the real needs to establish a PEPT center are what I just hinted at.

You need some sort of detectors. You need some sort of tracers. And the beauty of this is that both these things should be readily available at just about any kind of academic medical center or a research institute that has access to the medical institution, because this is again just borrowing technology from medical imaging. We are using PET scanners. This was something that commonly found in a hospital setting, as well as the radio isotopes that would otherwise be used for imaging someone's insides.

And that kind of brings us to where we're at VCU. So, at VCU, I am working with Lane Carasik in the Mechanical and Nuclear Engineering Department. And at VCU along with kind of our research and engineering side of the university, there's a fantastic medical center. And so, what we are working on is we started a partnership with the Center for Molecular Imaging at VCU, so this is out of the college of medicine, to set up effectively a PEPT center.

And what I am excited about is the PET scanner that we have access to through the CMI, the Center for Molecular Imaging, is this newer generation preclinical PET scanner, the Mediso Multi-Scan LFER. It kind of combines a lot of the advantages of that cylindrical PET array with a touch of modularity that I've previously not gotten to work with. And that is that you can actually pivot this board to allow imaging of test sections at different angles.

This could be now look at like vertically oriented test sections, things, slanted in that nature. And this is going to enable kind of a whole new generation of measurements with PEPT. And what we want to do first as we are setting up this PEPT center is look at things like a vertical packed bed geometry at higher Reynolds numbers. So, something with very direct applications in the nuclear world, understanding flows in these – for pebble bed modular reactor systems.

The current timetable has us starting those experiments early next year, sometime early mid-2021. And then beyond that continue to do experiments using these facilities in support of nuclear thermal hydraulics design. And I am personally quite excited about where we are going moving forward with PEPT. And I think we've been able to see that – this technique has been around since the early 90s, but a lot of recent work has been done to really push forward what can be done with PEPT.

And I hope that we are able to continue to employ this for measurements in these opaque systems, systems with kind of complicated geometries and enable new measurements for a number of different fields. And again, I'll touch on Tennessee. A big focus was on multiple particle tracking and what we can now do with that. I am excited for the experience we've been able to do and what we do moving forward. And that's kind of where we're at VCU is we want to take these techniques, take a new facility, a new scanner and see what we can do in advancing PEPT for advanced reactor design.

I want to thank definitely the groups at Tennessee, Art Ruggles, and Kate Jones, my other advisor, as well as Lane and everyone at VCU as we push forward in the PEPT frontier. Thank you all for your time. And I now welcome any questions.

Berta Oates
Thank you, Dr. Wiggins, for your budding expertise, shall we say, in this field. During the introduction, it was noted that you were the Pitch your Speech winner from the ANS winter conference. And we look forward to hearing much more breaking things from you in the future. I think you have a very, very bright future. It was a very incredible presentation.

While questions are coming in, if you have questions, please go ahead and type those into the questions pane now. And while those are coming in, we'll just take a quick look at the upcoming webinars. In January after the after the New Year, a presentation on MOX Fuel for Advanced Reactors. In February, Overview of Waste Treatment Plant, Hanford Site. And in March, Introducing New Plant Systems Design Code.

So, if you have questions for today's presenter, please do go ahead and type those into the Q&A pane. I don't see any questions right now. Here we go. Bear with me a minute. I am trying to get this screen to enlarge a little bit, so that we can – so there’s a question of who attaches the F-18 particles? Is it a radio pharmacist doing it?

Cody Wiggins
No, it's usually me. We started out with – we did this research under a radio chemistry center. So, at the beginning of all this, it was rad chemists showing us how to do it. It's a fairly simple procedure, just soaking tracer particles in an F-18 solution and then cleaning them off in a micro centrifuge. Any sort of transportation of the radioactive material is done by radiation safety specialists. But otherwise it is just our humble researchers.

Berta Oates
Thank you. How do you label yeast cells?

Cody Wiggins
Man, that's a fun one. That's a good question. So, this was done in collaboration with microbiologists at the University of Tennessee. So again, I was the one doing the direct labeling. And actually, in order to do this,

we have to genetically modify the yeast cells so that they could take in fluorine because yeast wants to naturally eat up this fluorine, but they'll eventually spit it back out because it's toxic to them.

And the microbiologists genetically modified the yeast cells, so they would take in the fluorine but could not spit it back out. So then after this procedure was done, we could then do the labeling. Essentially the same as how we do our particle labeling. We introduce yeast into a fluorine solution with some – I guess it was a glucose buffer to encourage the intake of fluorine.

And then you kind of run through a microcentrifuge filter out everything but the yeast cells and then just a series of dilutions you could isolate a handful of yeast cells to add into your system. There's a paper by my colleague Seth Langford. He would have been the first author on that. It can be found kind of describing that method in more detail.

Berta Oates
Very interesting. Thank you. How can PEPT be applied to two-phase flow?

Cody Wiggins
So, I'll answer that in a couple of ways. I'll take the easy way out first and that's when you say two-phase flow, if you are referring to like particle liquid, then it's a very natural translation because that's one of the places where PEPT has really shown – not in my own research groups but elsewhere is you are looking at kind of a solid liquid flow with very high volume fraction of solid.

PEPT does a very good job of tracking the solid phase in that. As far as two-phase flow for gas liquid, PEPT has been used to look at things like interaction between the liquid and solid phases by tracking tracer particles that – the tracer particles are neutrally buoyant in the liquid phase unless they effectively track the liquid phase.

PEPT has also been used in conjunction with like PIV to track bubbles, have like the PIV tracking the bubbles in the multi-phase flow. And then the PEPT is tracking the liquid phase. So PEPT has been used some in two-phase flow, but this I would say is still kind of in its infancy, still working out, everything that can be done.

There's potentially an interesting application regarding difference in positron range in the liquid and gas phases of two-phase flow. In the future we hope to be able to exploit that to maybe track the interface between the gas and liquid phases but we're not quite there yet. So, in short, yes, it can be applied. To what extent? We're still working that out.

Berta Oates

Thank you. How much time does one have between F-19 and running the experiment?

Cody Wiggins
So, the F-18 gets delivered by some sort of radio pharmaceutical supplier in a requested amount. And they tailor it to where you order. I am getting 30 millicuries at 8.00 a.m. or something of that nature. And for our experiments, we were typically getting the radiopharmaceutical from the supplier and probably had it in the flow loop in about an hour. And that is taking into account activation time, transportation to a different facility, again, that being done by radio – radiation safety techs, and then injection into our flow loop.

You probably have about – let me think. So, the half-life of F-18 is about two hours. Realistically, if there is a two or three hour gap between activation and insertion into the flow loop, it wouldn't create a significant reduction in data quality.

Berta Oates
Thank you. Do you start with FDG or some other chemical form?

Cody Wiggins
So, for our purposes we specifically do not start with FDG. So, we have – what we use is kind of the precursor to FDG in the radiopharmaceutical production line. And that is – there's an aqueous solution of F-18 ions. So, this is kind of what's directly taken off of the accelerator in most kind of, I guess, radioisotope production facilities. So, this is water usually enriched with oxygen 18 that gets bombarded in a proton beam to create this solution of F-18 ions floating around in water.

Berta Oates
Thanks. How do you distinguish the positions of each tracer in your M-PEPT algorithm, in your P-17?

Cody Wiggins
Right. So, within the algorithm, what we are using is a local maxima search to find where is each tracer. Kind of a rough estimate is – let me see. Do I still have control over the slides?

Berta Oates
Yes.

Cody Wiggins
I think you are referencing page 17. See if I can get back there. But I'll talk as we do that. So again, we take all of the lines from an individual time step and we trace them on to this 3D grid.

So, once we're in this voxel grid, we effectively have an image. We call it 3D image of the tracer. So now we have this 3D image of a tracer. We apply a kind of some smoothing filters like you would do in image processing to crisp up the image and then we do a local maxima search.

And this is essentially just going through each voxel in the dataset and saying am I above some threshold value? And am I the highest value voxel within – depending on the experiment within four or five neighbors? So, saying, am I of greater line crossing value than anybody around me? And so, any voxel that matches those criteria is considered a local maxima and then we do Gaussian fitting about each local maxima to, I guess, more precisely find that position of the tracer.

Berta Oates
Thank you. In many of your application, what size of your liquid – what's the size of your liquid tracers, the minimal size of liquid tracers you can achieve now?

Cody Wiggins
So, we are – yes, you are right. You reference the different applications there. It's application dependent. We're typically using tracers of the order of 100 microns up to 1 millimeter. So, in an application where we're not that worried about very small features of the flow field, we'll use the larger tracer because it does give us better time resolution. Because it has higher activity, we can do the reconstructions more frequently.

In things like – I showed the packed bed experiment where you have very small flow features to resolve. We want to use that smaller tracer. So, you say that the smallest tracers we've used were – well, I guess, the smallest tracers we used were the yeast cells, but the smallest engineering application tracers we've used were I think 90 microns in size. You could go smaller.

There are smaller forms of the same hydroxide form ion exchange resins that we are using for tracers. I think down to 10 microns you can buy them from various chemical companies, but the sacrifice there is you are losing some resolution because you are not able to pack on as much activity onto each individual tracer.

Berta Oates
Thank you. What's your estimate on how long you can run an experiment and still get good results?

Cody Wiggins
Right. So again, going back to, I guess, your previous question there of the time between receiving the radioisotope and starting the experiment. That does matter. But assuming you get the radioisotope there within an

hour or so, so it's kind of typical of our experiments, you kind of have two different competing factors. So, if you are only really concerned about the decay of your radioisotope, you can get meaningful experimental data for two to three half-lives, so four to six hours of data collection. However, if – I mentioned briefly that we use deionized water. And the reason we had to do that with this specific radio labeling technique is if you don't use deionized water, those ion exchange resins will start trading off their F-18s, which is what we wanted to have, with chlorine or some free ion in the water. So, you get this leaching effect.

So, whenever we – if you are using, say, tap water to do these experiments, you would get 10 minutes of data collection, because eventually your tracer just will leach out all of its activity and pick up other stuff. So those are kind of the two extremes of that spectrum. So, depending on the working fluid being used.

Berta Oates
Thank you. Does anybody have any more questions for Dr. Wiggins? If two tracers is very close, it's hard to tell each other the minimal distance of your tracers and your algorithm can distinguish this?

Cody Wiggins
Right. So that's one of the really fun thought experiments when we're doing our – well, thought experiments and real experiments when we are doing our kind of reconstruction algorithm qualification. So, the physical answer for our current reconstruction method is about 2 millimeters. Below that, it starts to become fuzzy. And what that's set by is when we are doing –like I show the same slide, when we do this tracing of lines on to a grid, we have to set up some finite grid size and we're typically – again, depending on the application, depending on how many flow tracers we expect to be looking for in a given data set, typically these voxels are cubes of side width 0.5 millimeter to 1 millimeter in physical space and you can't really resolve below 2 or 3 voxel widths.

Yes, below 2 or 3 voxel widths, these two clouds start to look like one big cloud of a line density to the algorithm. So again, down to about 2 millimeters. Below that, the algorithm will get confused. And what will happen – as far as flow statistics, it doesn't affect the data too much because what will actually wind up happening is if you have two tracers, one of them is inevitably going to be of slightly higher activity than the other, what will happen is the algorithm will just track the one that is of higher activity as it keeps moving and the one that is of lower activity will just get lost for a few timeframes and then will get picked back up a few milliseconds down the road.

Berta Oates

Thank you. That's all I see in the question pod currently. If there are more questions, please go ahead and type those in. How are you set for time Cody? Do you have time if more questions do come in?

Cody Wiggins
I think I am good until – I guess depends on what time zone we're in. I think I'm good for you know another 15 to 30 minutes.

Berta Oates
Great. Okay, so if there are questions, please go ahead and continue typing those in. And if not, I do want to take another opportunity to thank you for your time and effort to put this presentation together. It's a very interesting topic and it's so far-reaching between the sciences, the engineering, and the biology. Thank you again for your expertise. We do look forward to your future. I think you have a very bright and outstanding future.

Cody Wiggins
You are very kind. I mean thank you. I'm excited for this opportunity. It was not something I expected when I signed up for Pitch your Ph.D. last winter. So, this has been a pleasure. Appreciate the opportunity.

Patricia Paviet
Yes. And I would like to echo, Berta, a very, very interesting presentation, Cody. Thank you so much. And the same, you are one of these – the first for the ANS Ph.D. competition winner. We will have another one. I think she's scheduled in around May or June 2021.

It's very important for us to have also the junior scientists, the junior workforce showing what they are doing. So, we will look what you are doing in the future. Thank you so much again, Cody.

Cody Wiggins
Thank you.

Berta Oates
With that, I think we'll go ahead and end the presentation and wish everyone a good and safe day.

Thank you.

Patricia Paviet
Thank you everyone. Happy holidays. We will start again the series in January 2021. Happy holidays and stay safe.

Cody Wiggins
Excellent.

END