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PROFESSOR: So let's begin to examine our assumptions having to do with the transport of respiratory droplets in a well-mixed room by thinking about effects of fluid flow and transport going beyond a well-mixed room.

So to begin thinking about this problem, it's instructive to think of examples of simpler flows, in particular the canonical problem of flow past an object-- for example, a cylinder.

Here I've shown a cylinder placed in a uniform flow field with increasing speed and fixed object size.

So as you can see, at low speeds, the streamlines are fairly reversible and simple looking.

And at high speeds, you end up with very complicated turbulent flows.

A very simple parameter controls the transition between these flow regimes, which is the Reynolds number.

This is a dimensionless quantity, which is a property of the fluid, which includes the kinetic viscosity, for example, of air.

And I'll just write this, kinematic viscosity.

And it has a measure of the flow speed.

So we'll call that U. So the magnitude of the background flow here is U. And it has some information about the geometry, in particular the size of the object.

So for example, we could define this based on, well, let's just say, some length scale L, which could be, for example, the radius of the cylinder.

And in the case of this cylinder that I've shown here, if the Reynolds number is less than around 10, you're in this regime here of so-called creeping flow where you can see the streamlines are very simple looking.

And they are reversible.

So they kind of smoothly conform to the object.

And you can run the flow in the backwards direction.

You'll get exactly the same streamlines.

But once you get to a Reynolds number of around 10, then you start to see different effects.

And that's because the physical interpretation of this quantity is the ratio of inertia, which is the tendency for fluid to want to keep moving in the same direction due to its mass that has been set into motion, relative to viscosity or to viscous stresses.

And that's the tendency for the fluid to have some friction with itself.

If you start to move a piece of the fluid, other elements of fluid nearby are pulling back.

There's some friction.

And it impedes the motion.

So whenever inertia is getting bigger than viscous stress, we start to have a tendency for the fluid to want to keep going in the same direction.

And it can lead to very complicated flows.

In particular here, the first thing that starts to happen is the fluid kind of whizzes past the cylinder and then starts to have a recirculation on the back side.

So this happens around Reynolds number equals 10.

So if you have Reynolds number greater than around 10, you have some vortices are created.

So it's no longer an irrotational flow.

It has some obvious closed streamlines.

If we increase the Reynolds number further, like in this situation here, we get to Reynolds number bigger than around 90.

Then those vortices themselves are starting to spin fast.

And they also have some inertia.

And they start to separate.

Also the fluid is pulling those vortices away.

So we have vortex shedding.

And that happens in an unsteady fashion.

So what happens is there's-- one of these two vortices goes unstable first and peels away and starts to move downstream.

The other one kind of takes its place.

And it's almost like a flapping flag kind of motion, where a train of vortices is released.

So this is an unsteady situation.

And this is called a vortex sheet.

But it's basically an array of vortices that are being released in a time-dependent fashion.

And at first, that's a fairly regular process when the Reynolds number is on the order of 100.

But if you keep increasing the Reynolds number, that process becomes more and more chaotic until there's a transition to turbulence, which is a fully chaotic, heavily-mixed flow.

And that happens through an instability around Reynolds number of a 2,000, where you have a turbulent wake.

So behind the object or the obstacle, there is a steady stream of turbulence where, as I've tried to sketch here, you have vortices and eddies of all sizes.

So there are eddies like I've shown here that are at the scale of the cylinder, but then much, much smaller ones, too.

So it's a very complicated, time-dependent flow field.

So we can see here, the Reynolds number has a big effect on the types of flows that are generated and obviously also on mixing as you go from low to high Reynolds number.

So let's think about how that would change in the setting of indoor air.

So let's look at flow.

Let's look at airflow in a room.

So let's think about the different scenarios we could have.

So maybe our first scenario would be we have all the windows closed.

There's no movement in the room.

It's essentially a still room.

But as we've discussed earlier, there's still some air change with the outside.

So air is still leaking to the outside.

There's still a little bit of instability and movement also from thermal effects, which we'll talk about shortly.

So there is a little bit of flow in the room.

And in particular, let's just ask ourselves what happens if we have a little bit of air exchange with the outside, which is this flow rate Q that we've discussed, but in the case of natural ventilation with closed windows.

And in that situation, we've used as an estimate that the air change time, or air change rate, might be on the order of 0.3 air changes per hour, which corresponds to 3 hours' time to have the room air changed.

So that's a pretty slow pace.

If you consider a room whose height is 2.7 meters, just to put a number on it, and you have that air change rate, then the average velocity in the room is on the order of 1 meter per hour.

So that's a pretty slow pace.

So to go 1 meter, it's going take a whole hour, so very slow.

So you think, not much interesting is happening.

But if you calculate the Reynolds number for this situation, the Reynolds number is actually 110 with those numbers.

And that's already putting us in the regime of not only forming vortices, but also having some vortex shedding.

So even when a room is rather still, and there's just some very gentle movement of air out the windows, or cracks around the windows and other places where the room may not be tight, or from some other minor movement going on in the room, we already expect to see some unsteady vortices and movement of air in that room.

But the situation gets more-- gets much stronger if we now move to having ventilation.

So let's imagine that we have an HVAC unit on top-- maybe, let's say, an air conditioner, which is blowing air into the room perhaps from somewhere above.

So now we have a flow which is going into the room.

It still has to leave somewhere, let's say, through an outlet vent.

And in this case, the flow rate might be a lot higher.

So let's imagine, now, we have lambda a would be, let's say, 8 air changes per hour.

And this would be looking at a typical case of mechanical ventilation.

And what we really care about here, by the way, is the total flow rate.

So we're not interested in just the outdoor air.

So what I really want, I should mention, is lambda bar a, where that is the total air change.

So lambda a bar, we'll define as the air change due to just the fresh air-- so that was the Q over V-- plus the air change due to the filtration flows.

So there is sort of this recirculating flow-- and we've written that as Q-- the outdoor airflow plus the filtration airflow divided by volume.

So I just want to make sure we throw that in there, because you can get some flow going also by having a HEPA filtration unit in your room.

And there's circulation going on from that.

And that does contribute to mixing.

And so if we now calculate what is the Reynolds number, we're now getting up to around 2,000.

And that's interesting, because that is already getting to the regime of turbulent flow.

So just the velocities and flows that are generated in the air from typical air conditioning or even gentle fans will lead to turbulent flows in the room.

And turbulent flows are very effective at mixing.

So that's one reason we might expect to see strong mixing.

So what this actually looks like is-- imagine there's a person in the room.

There could be a table and a chair, some kind of obstacles in the room.

And even if nobody's moving, just the flow through the room is causing some turbulent wakes and vortex shedding.

And there can be some circulations, such that you have some fairly significant inertial effects leading to mixing in that system.

Now, we can also ask ourselves, what about other ways that momentum is imparted to the fluid in a room with people in it?

Well, it could be, for example, human movement.

So what if we have-- let's think about what the Reynolds numbers might be for that.

So if we have human movement-- let's say, for example, I'm moving my arm.

Or I'm moving my head.

I'm not even talking about running or really moving fast.

But let's just think about this kind of a motion.

I might be moving with a velocity anywhere from 10 centimeters, or 0.1 meters, to 1 meters per second, right?

So I could easily go 10 centimeters in 1 second.

But I could maybe go a little faster.

And I'm moving a part of my body, which might have a length that scales from, let's say, 10 centimeters to 1 meter.

So I'm moving maybe my arm or my hand or my head.

So if we take this range of values here and ask, now what's the Reynolds number, then the Reynolds number is around 10 to the 3 to 10 to the 5.

So and you know this.

If you have a room where there's some smoke or some dust particles that you can see in the sunlight, just take your hand and move it like this, even fairly gently.

You're going to see very complicated turbulent flows in the wake of that movement.

So basically, anything going on in the room in terms of movement is leading to substantial complexity in the flow fields, which contributes to mixing.

Another one to think about, which we will come back to, is human respiration, so the fact that you're breathing.

So we will come back to this term more carefully.

But we can still think about it in terms of the Reynolds number right now.

So if you imagine just the flow that is leaving your mouth-- so in this case your length scale is on the order of 1 centimeter.

So maybe the area of your mouth that's open is maybe several centimeters.

And the velocity of your breathing depends on how heavily you're breathing and what your activities are.

But it's on the order-- so if I write this as the velocity U-- I should have written this as a U as well, from actually over there.

So if my velocity scale is around 0.5 to 2 meters per second-- that's a typical respiratory velocity-- then now we find the Reynolds number is on the order of 10 to the 3 to 10 to the 4.

So again, all these activities of breathing, motion, anything humans are doing in the room, even just sitting there and breathing is leading to Reynolds numbers locally that are on the order of thousands or tens of thousands, which means that we are seeing turbulent flows in the vicinity of those motions.

So that doesn't mean that those flows are enough to mix the entire room.

But certainly in the vicinity of a person, there's a lot of mixing just from the natural movement and respiration of that person.

And when you add into that the mechanical ventilation, there can be very significant inertial mixing going on in the air of a room.

So in this simulation, courtesy of Saint-Gobain Ceramics and Plastics, we see an office space containing a number of workers sitting in cubicles.

And one of them is an infected person emitting infectious aerosols.

And the simulation shows you how those aerosol particles are transmitted through the room by forced convection, where the orange and white squares represent ducts of inflow and outflow in the mechanical ventilation system.

This video shows the effect of motion and also respiration leading to turbulent flows by forcing the air to move at a high Reynolds number.

So in the case of motion, we see a turbulent wake behind the moving person.

And for each breath, we see a turbulent plume emitted by the momentum transferred from the breath.

These images are taken by a schlieren imaging method that looks at differences in the density of the air and visualizes the texture of the patterns that are formed in the density.