Danielle (00:14):

Dr. John Shelton is an assistant professor in the Department of Mechanical Engineering at Northern Illinois University. He is currently performing research in a variety of topics that include additive manufacturing, sustainability and renewable energy, and advanced nanomaterials used in thermal energy storage applications. He received his bachelor's and master's degrees in mechanical engineering from North Carolina, A&T state University and his PhD in mechanical engineering from the University of South Florida. Afterwards, he was in the department of energy post-doctoral research associate in Carnegie Mellon University. Today, Dr. Shelton will be talking about nanofluid, thermal dynamics and heat transfer.

Dr. John Shelton (01:08):

Thank you, Danielle. Well, welcome everyone to my talk. I'll be talking about nanoscale thermal energy storage for space applications, talk a little bit about the research that I've done and how it applies to space applications. So when we think about space aircraft, a lot of times we think about the fact that the emptiness of space is very cold when in fact there's a lot of ways in which energy can be generated within various space aircraft. So, for example, here I have the international space station. Heat is encountered with the space station due to solar irradiation from the sun, where in some places we can get as hot as 121 degrees C or as cold as negative 157 degrees C, depending on where we are relative to the sun.

Dr. John Shelton (01:58):

Those huge solar rays that you see in that image over there is our electric electricity generation system, and all the electricity that's generated has to power a whole host of electronic equipment, sub-equipment, for example, a lot of the avionics, a lot of the experimental systems, that are used to conduct the experiments that the astronauts have to perform. All of that generates heat.

Dr. John Shelton (02:24):

I have one of those pieces of equipment here that's just listed there. This space acceleration measurement system, too, within just the control unit we have electronics control, mass storage, mass storage power, and control subpanel control panel subsystems, and when they're all operating, they're generating roughly 330 Watts of heat in that system. And, that's just one system and one subsystem of just one part of a measurement system, and we take all the other components, actually, there's a lot of heat that's being generated. And, we have to also take into account the fact that there are humans aboard.

Dr. John Shelton (03:05):

We as humans generate a lot of heat, whether we're just sitting down at rest where we generate between 600 and 1,000 Watts of heat, or if we're doing some sort of moderate exercise. For example, here, someone has done some research here and they said that for 30 minutes of moderate exercise where we're taking in as much oxygen, 75% as the maximum amount of oxygen, that we would normally take at a particular size, we're generating between 1,000 and 2,000 Watts of heat just by ourselves. So there's a lot of heat that's being generated in the space station.

Dr. John Shelton (03:44):

Now, there are other types of spacecraft. We have here a CubeSat. CubeSats are much smaller than our space station. We're talking about on the order of centimeters, 10 by 10 centimeters, in the plane. And, depending on the size, it could either be 11 centimeters in height, or maybe even 30 or 40 centimeters in height, still considerably a lot smaller than what we would normally assume what's going on at the space station. Despite the size, we are still generating a lot of power, and we're consuming about 200 Watts of energy, and all of this is being confined in about a thousand cubic centimeters, which is roughly about the size of your standard water bottle.

Dr. John Shelton (04:29):

So, all of that heat is concentrated in a very small space, and we have to find a way to dissipate that heat. And then, for example, here in the next few years or so, NASA is planning to go to the moon or Mars. So, a lot of the issues that we saw in the international space station, as well as for the CubeSats, we're going to see at the Artemis crew module or some of the other components that are going to be associated with this particular flight. We're still going to have our solar irradiation. We're still going to have electricity generation that's going to generate a lot of heat with all the electrical components and sub components. And, then we're also going to have humans on board that are going to be generating heat.

Dr. John Shelton (05:12):

So, with all this heat that's being generated in a variety of aircraft, how do we dissipate it? Well, we have a variety of different thermal control systems, depending on where we are. For example, in the International Space Station, we have multilayer insulation that kind of coats the outside of our modules and forms an insulation barrier so that all the incident solar irradiation doesn't get to pass through into our surface. And, then any of the heat that's generated inside doesn't leave.

Dr. John Shelton (05:46):

We have heat exchangers that involve heat transfer fluids, such as water, ammonia, air. And, all of that is basically our traditional heat exchangers where we're trying to take away heat from one area and take it to another. In this case, for example, we would use water with a 17,000 RPM impeller that actually primes or drives our fluid from one location to the other. And, some of the very high heat-generating materials actually have cold place associated with them, which is just another form of a heat exchanger.

Dr. John Shelton (06:22):

All this heat has to go somewhere. So, we have these radiators that are composed of honeycomb aluminum panels that take the heat that's generated within our system and dissipates it out to the atmosphere. For CubeSats, since we're talking about things so small, we can't have heat exchangers or things that have a lot of mechanical components because we just don't have the space for them.

Dr. John Shelton (06:47):

So, we have to think of creative ways to dissipate heat or even remove heat. So, we may have some films or coatings that may insulate or dissipate heat. We may utilize sun shields or sun shades, thermal straps, thermal loopers, heat pipes, or thermal energy storage units, or phase changing devices, which is kind of where we are right now with this particular top. And, we can take some of these technologies and apply it to our Artemis crew module, because since we're dealing with a very long travel time, considering that we might be going to the moon or going to Mars with the Artemis crew module, we don't have a lot of energy to dissipate to use for active heat removal systems. So, we have to incorporate some of the passive thermal management systems that we are using, that we can see in our CubeSats.

Dr. John Shelton (07:43):

So, I've talked about active and passive thermal control systems. Let's talk about that a little bit further. So, when we're talking about an active thermal control system, we're actually requiring some sort of energy to drive our operation. So, we need some sort of electrical energy, some sort of energy that kind of gives us the power to actually operate our thermal control system. Because it has such active control, we're able to really fine tune the amount of energy that's required to maintain a particular temperature, given some specific specifications that maybe our component particularly needs. Unfortunately, it takes a lot of space, which is something that we don't have a lot of in these spacecraft, and also requires a lot of power.

Dr. John Shelton (08:33):

So how do we avoid that? Well, we have passive control systems. Now these passive thermal controls don't require any input power. It's not very expensive. It doesn't take up a lot of space. It doesn't take up a lot of mass and it's low risk. You know, we don't have any risk of any type of mechanical failure associated with the removal of heat, which is very important when we're talking about risk and longterm space travel.

Dr. John Shelton (09:02):

So, we are going to look at different ways in which we can utilize some of the thermal energy storage capabilities of certain materials to incorporate them into passive thermal control. But, before we do that, we're going to go into the classroom, because we're going to need to understand some information that we've learned maybe, or maybe we will learn eventually. So, you can see here a picture of our engineering auditorium at Northern Illinois University.

Dr. John Shelton (09:34):

I will encourage everyone to put on their mental caps and join, take a seat. And, as we embark on this little short mini-course on engineering thermodynamics, if you have taken engineering thermodynamics or you plan to, you've probably taken it from either one of these authors, Cengel and Boles or Moran and Shapiro. Those are pretty much the standard when it comes to engineering thermodynamics. We're going to take some examples from this and try to do an example and see if we can take some of those principles and apply it to our passive thermal control systems.

Dr. John Shelton (10:15):

So, here we have a property diagram. For those of you that have already taken it, I'm going to remind you, and for those that you haven't, I'm going to introduce it to you. Here we have an indication of the different possible states for any particular substance. We have a dome, and then to the left of the dome, we have what is called the compressed liquid region. To the right of the dome, we have the super heated vapor region. Under the dome, we have what is called the saturated liquid vapor region. And, all of these are specific states of a substance. In this case, the substance is water.

Dr. John Shelton (10:53):

So, we have compressed liquid, superheated vapor steam, and then we can have a mixture of the two under the dome that occur at the same time, based off where we are under the dome. We could have more steam over here or less steam over here, or maybe we could have an equal amount in the middle. Now, of course we have our critical point at the top, and these lines of constant value that we see cutting across on top of or going through this dome is a line of constant pressure. So anything along this line here has a constant pressure value. And, addition to that, as you cut across this horizontal line, it hits the Y axis at a particular temperature. This Y axis has a value of temperature. So, we have a particular temperature associated with this horizontal line. We're going to use this information to do a very basic problem, and then see if we can get some more information from it as it relates to our specific space application.

Dr. John Shelton (11:56):

All right, then, so we're dealing with water. We're going to look at what's going on here at this location where we have an F, and we're going to look at what's going on here when we have a location located at G. So, this is a particular state, and this is a particular state, both of which are lying on this line of constant value. So, that's a line of constant pressure. So, both of them have a pressure of basically 101.325 KPA, that's kilopascales. And, then, because both of these also occur on the same horizontal line, they're both going to have a temperature of 100 degrees C. Since we have two properties of our substance, we can identify a whole host of other properties associated with their substance. For example, we can determine the specific internal energy. We can look at the specific volume, which is what we have here in our X axis, and we can also identify the specific empathy. Each of these individual properties here can be substituted in our X axis so that we can identify whatever values that we're looking for.

Dr. John Shelton (13:03):

So, if we were to go to our back of our Cengel and Boles or Moran and Shapiro, we should see some tables there. There are also web book applications given to us by the National Institute of Standards and Technology that also give us the same information. Doesn't matter where we get it. We can still basically get the same values. So I did it for you. So, I'm going to just show you the results.

Dr. John Shelton (13:27):

At 100 degree C and 101.325 KPA, the specific internal energy at location F is 418.95 kilojoules per kilogram. At stage G, the specific kernel internal energy is 2506.0 kilojoules per kilogram. If we look at a specific volume, we have 0.01043 liters key per kilogram. And, for state G, we have 1.6734 liters key per kilogram. And, for the specific enthalpy at state F, we have 419.06 kilojoules per kilogram, and 26.75 kilojoules per kilogram.

Dr. John Shelton (14:19):

So, we can use this information to actually solve the thermodynamics problem, using the information that would normally occur right after we introduce this concept, which is the first law of thermodynamics, the conservation of energy. So I have this equation here. Conservation of energy tells us that energy in minus energy out is equal to the change of energy of the system. And, we're talking about the substance and the substance itself, so this is a closed system. So, we have heat in and work in, heat out and work out. The system itself has the energy associated with the internal energy, Delta U, any kinetic energy associated with the movement of the substance and any potential energy associated with the change in height of the substance.

Dr. John Shelton (15:06):

I will leave this to you if you want to explore this a little further, but you can do a whole lot of simplification here and assume that one of the work outs is boundary work associated with the change in volume. And, that's what we end up here with this term, the boundary work, along with their internal energy. We can combine those terms together to give us enthalpy. We can extract out the mass from this big Delta H, and we get our change in state HG minus the state HF, which in the back of the book, at any table, they have a specific value here called HFG, which is just the difference between the two. It turns out that HFG has a specific name for it. It's called the latent heat of vaporization. So, that's the amount of energy it takes to get us from our saturated liquid point, state F, to the saturated vapor point, state G.

Dr. John Shelton (16:03):

And, it's roughly 2256.54 kilojoules per kilo. Great. Great review. However, in engineering thermodynamics, they're mostly concerned about using the change from liquid to vapor for power generation and our ranking cycles and things like that. But, we're more concerned about using this information for thermal energy storage. So, we're going to have to expand this diagram a little bit further to be able to look at what happens when we transition from a solid to a liquid. So, this is our diagram. It basically tells us the same thing that we saw before, except that our X axis has changed. And, so now we have the energy that it takes to go from liquid to steam, and then we also have this region here that is the amount of energy that it takes to go from solid to liquid. So, solid water is ice. Liquid water, of course, is water.

Dr. John Shelton (16:59):

And, we see that that energy is much smaller than it is for water to steam. That little region right here, the energy it takes to go from ice to water, is called the latent heat of fusion, and that's roughly 333 kilojoules per kilogram, or if we want to convert to the units in the X axis, is roughly about 80 calories per gram. Awesome.

Dr. John Shelton (17:22):

Now waters are really good thermal energy source system, storage material is used for long term thermal energy storage, seasonal thermal energy storage, but for space applications, it's not really good. So, we have to look at other materials, and some of the other materials include molten salts, organic compounds, like long carbon chains, or even metals. And, all of this is focused on transitioning from a solid to a liquid or from a liquid back to a solid.

Dr. John Shelton (17:56):

In the case of metals, sometimes it's converting from one phase of a solid to another phase of the solid and converting back. We don't even have to worry about a liquid at all. There are some drawbacks, but that's another topic for another time. The reason why we have candles here is because candles are actually a really good organic compound to do thermal energy storage. It's a long chain, long molecular chain system, that melts when fire hits it. And, then it re-solidifies when the heat is gone. The reason why I bring this up is because M&Ms is a really good way to visualize thermal energy storage when we want to encapsulate it. It turns out that chocolate is a really good material for thermal energy storage. It's just like wax. It just tastes better, and we can encapsulate it with the hard candy shell so that it doesn't prevent it from melting on the inside.

Dr. John Shelton (18:54):

So, we can take this application and apply it to what we're trying to do, which is to try to take the characteristics of our thermal energy storage material and encapsulate it so that it is useful for space applications. So, I have some ways in which we can do it. We can do it through the microscale, which is between 1001 and 1000 micrometers, and then on the nanoscale, which is what we're doing. We're doing from one nanometer to basically about a thousand nanometers. All right, here are some other investigations that have been done where we look at phase change materials that could be used to store energy, and the shell, the hard candy shell that is used to kind of encapsulate it.

Dr. John Shelton (19:41):

But, what we did is we did our own thing. So, we did our laboratory synthesis and analysis, and then we did computer simulations, and I'm going to speed right through this real quick so that we can get out of here in about three minutes.

Dr. John Shelton (19:55):

So, first things first, we went into the lab. We actually synthesized the core of our material. So, to synthesize the chocolate, if you want to visualize it, it turns out that the synthesis process is almost like washing your clothes in the washing machine. Now, we take the oil; we take the dirt. We put detergent in it. The detergent encapsulates the oil and encapsulates the dirt, and normally when we're washing that encapsulated dirt washes away with our washing. But, what we're going to do is we're going to deposit around the detergent so that it creates the shelf for us. And, this is the process that we do. It's called the sol-gel process, and that's all the details for it. Then we did a whole host of analysis, whether it's SCM, TM, FTIR, DLS, DSC. I won't go into too much detail with that, but here is our result.

Dr. John Shelton (20:51):

As, a matter of fact, this picture right here is the picture that we had beginning of their presentation, where we actually synthesized these encapsulated phase change materials. This gave us an idea of the size of the materials that we had. Some of them were pretty big, and some of them were kind of on the order of 100 nanometers. Next thing we did was we looked at the shell to see if the shell was pretty thick or pretty thin. As we can see here, the shell thickness was on the order of seven nanometers. We were able to get a shell of about 20 nanometers as well. And, in some cases we weren't too successful in generating the shells, and we have some reasons for why that happened, and this is a little bit more about that.

Dr. John Shelton (21:35):

And, then what we did was we looked at the chemical composition to make sure that we actually made what we think we made. So, this is our core material, palmitic acid, or palm oil, and this is our shell, SiO2, or pretty much glass or sand or anything like that. And, we have these vibrational peaks that is sort of associated with each of the bonds that are within our system. And, we can basically identify the vibrational frequencies for each of them. And, now here, here is kind of the same graph that we saw at the beginning of the presentation, but kind of inverted. If you remember, this temperature was on the Y axis, and the heat was on the X axis, but it's basically telling us the same thing. To the left of the peak is solid; to the right of the peak is liquid, and the peak itself is the amount of energy associated with taking our solid to a liquid state.

Dr. John Shelton (22:29):

This is an unencapsulated material. And, then each of S-2, S-4, S-6 and S-8 are encapsulated materials. We have a shell around it, and as you can see here, we really didn't get any good results because the shell actually decreased the amount of energy that we were able to capture because of... Well, that's what we tried to investigate next. Why did it reduce the amount of energy that was possible for it? So, then we went to computational analysis. We did some advanced molecular dynamic simulations that kind of simulate it.

Dr. John Shelton (23:06):

We didn't use Silicon dioxide and the long chain palmitic acid; we just used something very simple, and we were able to replicate the melting temperature associated with it. We saw the structure of the solid and liquid to see that we actually got some sort of liquid during the phase change, and we're able to replicate the enthalpy of fusion, what we talked about in those beginning slides, to kind of correspond to what we saw in both in other molecular dynamic simulations, as well as other experimental results.

Dr. John Shelton (23:38):

So, here we have our core melting. Cool. But, what happens when we have the core, which is blue, encapsulated by something that's our shell? Well, it turns out that we end up finding out something very interesting. Our core ruptures our shell, and all of that's associated with what we've talked about at the beginning with the boundary work that's occurring with our material. It's exerting an external force or internal force on our shell, increasing the pressure, and is basically causing the shell to break.

Dr. John Shelton (24:15):

So, this brings us to what we're going to be doing next. We are not making M&M cookies or M&M cake. We're actually taking the concept of these encapsulated phase change materials and seeing the impact they have when they're embedded in other stuff. So if we wanted to put it into our spacecraft, how well does it dissipate heat, or how well does it absorb heat, and very high heat flex materials or high heat-generating materials? Does it impact in any way? And, we want to quantify that. And, that's where we are right now. We're definitely doing some more work with that. We're doing some more simulations, but this is where we are at this moment.

Dr. John Shelton (24:56):

And, that's the end of my presentation. We have a lot of students that have worked with us, did a lot of work at Argonne National Laboratory. Some help here at NIU with other professors, but that's the end of my presentation.

Danielle (25:11):

Thank you so much, Dr. Shelton. If anyone has any questions, you should be able to unmute yourself now.

Speaker 3 (25:17):

Hi, Dr. Sheldon. Question: How would you, or where do you imagine this going in terms of materials for space applications down the line? Where do you think your best candidates are going forward?

Dr. John Shelton (25:31):

Oh, so what we've been trying to do is we've been trying to embed these encapsulated phase change materials in thermal barrier codings for other applications. So, we want to apply the same principle for the space applications, especially for those passive systems that have some sort of a coding on them. We want to embed them on since they're so small. We think they could enhance the energy absorption at the surface without having too much material added onto the system.

Speaker 3 (26:04):

Very interesting. Thank you.

Danielle (26:07):

Okay. We do have one question in the chat. How would this material be implemented in a spacecraft? Would it be put in a thin layer in the walls of the craft? That's from James.

Dr. John Shelton (26:20):

All right. Cool. So what we would do is we would create a slurry or some sort of material that we could either paint on or spray on to our material to enhance the surface characteristics, to enhance the energy transfer or the energy absorption of the material.

Dr. John Shelton (26:40):

So, if we have a high heat-generating surface, we could code it with this material where we have, thinking again of the M&Ms with the cookie, we could have these M&Ms in the cookie on the surface. And, as the heat that's generated, we can have the energy absorbed in the M&M, and then we can use it for times when it is not generating the high heat to keep the material at a pretty much a constant temperature.