Scale Effects Analysis on the Thermal Hydraulic Behavior of Impinging Jets in Sodium Fast Reactors

Mr. Benjamin Jourdy, CEA, France (2nd Winner of the 2021 Pitch Your Gen IV Research Competition)

Berta Oates
Welcome, everyone to the next Gen IV International webinar presentation. Today's presentation on Scale Effects and Thermal-Hydraulics: Application to the French SFR will be presented by Mr. Benjamin Jourdy.

Doing today's introduction is Dr. Patricia Paviet. Patricia is the Group Leader at the Pacific Northwest National Laboratory. She is also the co-chair of the Gen IV International Forum's Education and Training Working Group. Patricia, I give you the floor.

Patricia Paviet
Thank you so much, Berta. Good morning, everyone, and good evening. We are very happy. I am very happy to have Mr. Benjamin Jourdy with us today. He graduated in 2019 from Ecole Centrale de Marseille in the field of Materials and Structural Mechanics. During his studies, he worked part time for the French Atomic Energy and Alternative Energy Commission, the CEA, at Cadarache Center, as an apprentice on the dynamic response of fuel assemblies in PWR under seismic excitation.

He designed the instrumental setup of EUDORE, a mock-up with three fuel assemblies at scale 1:2, and performed experimental campaigns in representative conditions of PWR.

Benjamin is currently completing his Ph.D. in the field of thermal hydraulics, on the subject "Scale Effects Analysis on the Thermal Hydraulic Behavior of Impinging Jets in Sodium Fast Reactor". His Ph.D. focuses on the buoyancy effects of the core jets in SFR after impingement of the Upper Core Structure, and their transposition from small scale mock-up to the reactor size.

I would like also to note that Benjamin won second place of the 2021 Pitch Your Gen IV Research Competition which was organized last year by the GIF Education and Training Working Group, and you can watch his video at the link that you have here.

Without any further delay, Benjamin, I give you the floor and thank you again for presenting this webinar.

Benjamin Jourdy
Thank you, a lot, Patricia, and thank you a lot, Berta, for organizing this event. Good morning or good evening, everyone, depending on where you are.

Today, we will talk about scale effects. First of all, I would like to say that the purpose of this webinar is to present another view on the scale effect issues we can have in physics and in the nuclear field and to present a methodology I am currently applying to sodium fast reactor during my Ph.D.

First of all, maybe it could be interesting to define the scale effects.

I think that I cannot change the slides. Okay, it is working.

First of all, I am going to provide a quick definition of what are the scale effects. It can be seen as a distortion of a physical phenomenon between a downscaled mock-up and a full-scale prototype. Scale effects, they usually come from a variation of the length L because when you change the length of a stem, you change the area because they are multiplied by the square of the length, and you change the volumes because they are multiplied by the cubic of the length.

An example we can have of scale effect in nature could be with the example of a mouse and an elephant. Let's take this example. We have a mouse that will be a size L. The area of the mouse will be described as a cubic of the size L and the volume will be – sorry – the area will be the square of the length L and the volume will be the cubic of the length. Now, let's say that we have an elephant that is 100 times the size of the mouse, so it is 100 L. The area will be 10,000 times this length L and the volume will be a million times this length.

It will lead to a surface-to-volume ratio that is 100 times lower for the elephant and we know that the surface-to-volume ratio is important when you are losing your energy with your environment when you have to keep your body at the same temperature. It leads to the funny scale effects saying that the mouse has to eat 100 times more than the elephant when, of course, relative to weight, just in order to maintain the body temperature. This is something we can verify in the nature.

Usually, the mouse has to eat the equivalent of its own mass every day, while the elephant only has to eat around 5% of its own mass every day. This is an example of just a scale effect we can have in nature. But, today, I am not here to talk about mouse and elephants. We will talk about hydraulic.

Scale effects example we can find in fluid mechanics, I am just showing two different kinds of scale effects. On the left, you can see a waterfall that is scale 1:30. On the left part of the left figure, you can see the downscaled mock-up, and, on the right, you can see the full-size prototype.

You can see that we have really different properties of the flow because even if we keep the same discharge between the mock-up and the full-scale prototype, we can see that we have air entrainment that is really different between them. It comes from a deviation of a dimensionless number known as a Weber number. But this is an example we can see with our own eyes. That's okay. We should be similar. We just replicate it at lower scale, but we can see it is completely different.

In a more mathematical approach, something we can see is about gas entrainment criterion. The gas entrainment is something you can have in your best tube, for example. This is something we can find also in sodium fast reactor.

This example of scale effects come from a study from Eguchi et al explaining that, okay, they were looking from a criterion of the moment we can start to have this gas entrainment and it was seen that the criterion used being the Froude number is changing with the scale ratio as we can see here. It is an example more mathematical of scale effects we can find. That's okay. We have different critical values depending on your scale. In fluid mechanics, this is more scale effects we can find.

But, today, we will talk about nuclear field because, in fluid mechanics, when I was showing you, for example, the waterfall, it is something pretty easy to study. But, in nuclear power plants, because today we will talk about thermal hydraulics in nuclear reactors, in nuclear power plants, we have a really complex flow, most of them being transient. Because this is fluid mechanics and thermal hydraulics, we have a lot of difficulties to establish closure laws.

The premise is that it is quite difficult and expensive to build a scale 1 reactor only to perform some tests. A really powerful tool we have in the nuclear field is the use of the numerical tool for scaling validation when we are trying to create new prototype or new design for experimental reactors. We are using the numerical tools but the numerical tools, as a code, need a validation and we are validating them with small-scale experiments which leads to the question, how can we ensure the validity of the small-scale experiments to a reactor size and how can we transpose these results.

Here, on the right, I am just showing you a quick methodology usually used to validate some codes using some separate effect tests for a better phenomenon understanding where we developed some model that we tried to improve, we validate with some experiments at not exactly small scale – with separate effect test and integral effect test in order to find a better code possible but we still have to evaluate some uncertainties and some transposition coefficient between the small-scale mock-up and the full scale prototype.

Could we please, because it's still not working for me, move to the next slide please, Berta. Thank you very much.

Today, we will talk most especially with the French sodium fast reactor problem we can have and why do we need to perform some experimental study to determine the scale effects.

First of all, let me talk a bit to you about the ASTRID Project. ASTRID stands for Advanced Sodium Technological Reactor for Industrial Demonstration. It was a project launched in 2010, where the aim was to build a French sodium fast reactor in CEA in Marcoule. Unfortunately, this project, a project to build a physical reactor, stopped in 2019. Instead, the CEA is working on a numerical reactor in order to simulate the whole behavior of the whole reactor. The premise, we are using codes. We will need some validations, of course.

Just to clarify, today, we will talk on – it's in that – the image has moved a bit. We will work especially on the hot plenum thermo-hydraulic. Today's presentation will only focus, if you take a look on the right, on what is in the red part, which means it is all the above plenum where we can find the upper core structure and the intermediate heat exchangers. This is the part of the reactor we would talk about today.

In this zone, I can already show you some simulations that were performed by Areva in 2013. It is, of course, numerical simulation of the velocity profiles as you can see on the left and then the temperature profile you can see on the right. This simulation, so we can at least have a first idea of the flow inside the zone. Of course, as I keep saying, we still need to validate code with experiments.

What we are doing, we have a mock-up in CEA Cadarache named MICAS. It is a downscale 1:6 of the hot plenum of the ASTRID reactor and it is a homothetic transformation, which can be seen as a linear scaling. Everything is reduced of a factor 6 on the side. Of course, all the areas are reduced by a factor of 36 and the volume by a factor of 216.

This mock-up represents, as I showed, the main component we can find in the hot plenum of a sodium fast reactor. We can find the core where, of course, we do not have a fission reaction here. We only can put some water to replicate the thermo-hydraulic behavior. We can find the upper core structure and the heat exchangers in the red zone. Also, to note that we are using water to perform our experiments instead of the sodium because it is easier to perform measurements in water instead of sodium because of its opacity.

Now, we will talk a bit about the kind of flow behavior we can find in a sodium fast reactor. This is the numerical modelization in the MICAS mock-up that is representative of what is happening inside a French sodium fast reactor or in the ASTRID reactor.

First of all, we start outside of the core. In this zone, we have 288 hot jets. When I say hot jets, it is 575 degrees in ASTRID, and it is around 60 degrees in MICAS. Then, these 288 hot jets are going through a porous plate and impinging the upper core structure. Then, in this zone, all the jets will merge, and they shoot into the vessel as one radial jet. Inside the vessel, we have a colder environment that will be around 550 degrees in ASTRID and around 57 degrees in MICAS.

Why is the environment a bit colder? It is because close to the core and in other parts of the core, to be exact, we have some cold jets. When I say cold jet, I am talking about 400 degrees in the ASTRID reactor and 10 degrees in MICAS. It has a low mass flow rate. As we can see here, it is in this zone that's where I am injecting some cold jets. It leads to a mixing temperature that is a bit lower than the hot jet ones, even if it is close because we have more mass flow rate going through the hot spot than the cold one.

Now that we understand that, okay, we will have a lot of jets impinging a structure and diffusing into the vessel. When the temperature is a bit lower, we can start to talk about the issue we have on this phenomenon.

The main issue I will talk to you today is that at low power operating conditions, we start to see a rise of the radial jets. When I talk about the radial jets in this presentation, it will refer to this zone, the jets that come from the merging of the 288 jets after impingement. In this zone – so here I am showing you some PIV experimental results on the MICAS mock-up. At nominal operating condition, we should have a jet going downward as we can see here.

But what appears at low power operating condition is that we can see that the jet is not going downward as it should, and it is even going upward. That can lead to some issues inside the reactor. The main issue we can talk today is about the consequences that the flow pattern inside the vessel will be modified. It will lead, first, to thermal oscillations leading then to thermal stress of the components. Of course, if you have some components that are targeting hot and cold and hot and cold, it will lead to some stress on the materials and it will reduce the life expectancy of the whole plenum of the reactor.

Now, the problem we are trying to solve today is under which condition does the jets rise and then, when we will start to understand the physical phenomenon, how can we transpose these results, from the MICAS mock-up to the ASTRID reactor. It is to the point – that's what I am discussing today that we need a scale effect analysis, and we choose to do it with an experimental approach in order to determine the scale effects and the transposition of this phenomenon.

Now, we talk a bit about the method we can have when we have to deal with scale effects and what is currently used in the literature.

First of all, we have to talk about what is the similarity. When we have a downscaled mock-up that is scale of one to lambda, lambda being the scale factor, in the case of MICAS, lambda is equal to six, we can achieve something that is completely similar to the real-world prototype, so in our case, to the ASTRID reactor, if we satisfy three criterions according to Heller.

First of all, we have to ensure that we have a geometric similarity, which means our mock-up has to be perfectly similar in shape, we should not perform some geometrical distortion, and it leads to the consequence, as I showed you with the mouse and the elephant. The length, area, and volume have to evolve with the scale factor being itself, the square of itself, or the cubic of itself, respectively.

Then, once you have the geometric similarity, you have to ensure that you get a kinematic similarity, which means a similarity of motion. It means that you have to get a constant ratio of time, velocity, and acceleration in your mock-up in order to be representative of the reality. Then, once you can ensure the geometric and kinematic similarity, you have to ensure that you get the same dynamic similarity. The dynamic similarity is a thing that we have to get identical force ratio at each point of option mock-up.

Unfortunately, for the people that have already been doing some fluid mechanics, we know that not all force ratios can be preserved. Most of the time, we have to select the most dominant one because each phenomenon usually has a dominant force ratio applying on it and then we have to consider the other one as negligible but sometimes we have too many force ratio that we have to take in account, and we have some of them that are not negligible. Of course, when you try to neglect some force ratio that should not be, it leads to scale effects. The whole problem comes from the similarity between a mock-up and a full-scale prototype.

We get some different scaling techniques. First of all, of course, the main point is to target the phenomena at both local and system level. When I talk about the local level, it is exactly what I am doing with my jets. First of all, we could perform a dimensional analysis. It is an empirical approach which means we will try to find some correlation and models to derivate similarity parameters which means we would perform some experiments and say, okay, if we work this way, then we can transpose this result from a scale to another and try at least to estimate some distortions.

Unfortunately, this empirical approach is that you cannot always have a strong confidence in this kind of approach so when you know how your system is behaving, you can use the dimensionless governing equation which is a more mechanistic approach. The dimensionless governing equation is with mechanics being known as mass momentum and energy conservation. Usually, you have to simplify the governing equation with your assumption on your flow and you can compare by putting it in a dimensionless form.

You can compare the non-dimensional terms between the model and the prototype in order to estimate what force ratio are you keeping and which ones are getting some distortion and evaluate the effect of the distortion. This is for the local level. Then, it is the system level that you have to deal with. Because from this approach, you can find some scaling laws from different governing equation with some dimensionless parameters you have to keep from a scale to another and you can then try to identify all the phenomena happening and rank then in a PIRT being a Process Identification and Ranking Table. This is how we deal usually in the nuclear field with scaling techniques in order to have its scale effects.

Now, we talk a bit about the Vaschy-Buckingham Theorem. For the first point, I was talking to you about targeting the phenomena at the local level. It is the empirical approach. The Vaschy-Buckingham Theorem is a simple and direct manner for the formulation of criteria for dynamic similarity.

Let's say, you have a physical problem, you will have independent parameters. These parameters can be the velocity of your flow. It can be the density, it can be the temperature, it can be a lot of parameters and you will have our reference dimensions, your dimensions being sometimes the temperature, the mass, the length. The Vaschy-Buckingham Theorem is just saying that you will find n minus r independent dimensionless parameters. It can be geometrical parameters. It can be force ratio. You will find some geometrical parameters even if your system is behaving like a black box. You don't really know what is the physics happening, you will see be able to find some geometrical and force ratio parameters.

Unfortunately, with this theorem, the relative importance of the dimensionless number remains unknown. It leads to an arbitrariness in determining the similitude condition because if you have a lot of dimensionless parameters, you are not able to say, okay, this one is more important than this one. This is why the Vaschy-Buckingham Theorem, this kind of empirical approach, is strongly criticized when you have more than six dimensionless parameters that you have to keep between a downscaled mock-up and a prototype.

Usually, what we are doing is trying to understand and find the governing equation of your system. As I said, in fluid mechanics, the most governing equations, the most commonly used equations are the mass, momentum, and energy conservation. Using this dimensionless equation gives you information about the relative importance of all terms you can find from a scale to another, and you can compare this force ratio.

For example, if I take here the Navier Stokes equation, if I decide to keep trying the Reynolds number, I can see the distortion that it will lead to the earlier number, to the Froude number, etcetera. One small hint about this technique is that the geometrical parameters are not taken in account. If you perform the geometrical similarity, it is not a problem. If you have to create some distortion, you will have no information about some ratios you should keep from a scale to another. But most of the times, the dimensional analysis is way more powerful than the Vaschy-Buckingham Theorem when the equations are known.

Now, let's talk about some scaling technique examples we can find in the literature, and we can find in other countries, for example.

First of all, the first scaling techniques, the most commonly used, of course, is the linear scaling. It is exactly what we are using with MICAS. It is just saying we keep exactly the same aspect ratio and velocity. We just do the exact replica of a downscaled mock-up. Unfortunately, while doing it, we cannot have a downscaled universe around our mock-up. We have some constants, universe constants, let's say, that will remain.

For example, by doing a linear scaling, the gravity stays the same on a smaller mock-up which means it can excessively distort the gravity effects. We can have an overestimation of some gravity effects by doing just the linear scaling.

When we have some issues that are dealing with gravity effects, we can use other techniques. I am just presenting one today that is known as the power-to-volume scaling, and I am showing you on the right an example. It is PKL. PKL standing for the German word for primary circuits of a PWR or Pressurized Water Reactor, and this is a mock-up you can find in Germany at Framatome in Erlangen.

The power-to-volume scaling technique is a powerful technique to keep time and heat flux because it is a scale 1 on the heat, it has a geometrical distortion, the height is a scale 1 but the volume, for example, on a scale 1:145, you will have no distortion of the gravity effects thanks to the same height, but you will have other distortion because you reduced the volume. It leads to excessive heat stored in the structure instead of in the flow and higher heat loads because you have a higher surface to volume ratio as we can have, for example, with the mouse.

We will lose more energy, so it is distortion you are creating but it is a perfect scaling technique when you want to study some accidents, for example, some natural circulation will have during loss of coolant accidents or other studies they can make in this facility. It is a distortion you can have when you have one specific issue, and you don't really care about creating new distortion because you have no distortion on your target phenomena.

You have other techniques that are way more mathematical. For this slide and the next one, I will be a bit quick because it is not exactly the point of the presentation of today. I am just showing you for the people that may be interested in this. For example, the hierarchical two-tiered scaling technique. It is a technique that's, okay, you have to perform a system decomposition. When you have a really complex system, you divide it into subsystems. Each subsystem being divided themselves into modules, constituents, phases, etcetera. You have to perform some scale identification. You will define some volume fractions, spatial scale, and temporal scale.

Then, first of all, you do a top-down analysis. You do a scaling hierarchy in each component, each module, etcetera, using the governing conversation equation. Then, you can perform a bottom-up analysis in order to get some scaling criteria and define the time constants you will get in each, let's say, of your box. It is a method. I am not talking too much about it. I will provide you some references at the end of the presentation if you are interested in that kind of method.

It is usually used and compared with other kind of methods such as the fractional scaling analysis. The fractional scaling analysis is an analytical approach for complex problems such as you can find in fluid mechanics, of course, but also in economy or in ecology. It is a strong technique when you have some variables that are getting influenced by convection problem, diffusion problem, or wave propagation.

When you have other issue with, for example, some scaling distortion because of time dependency, you have a recent innovative approach known as the Dynamical System Scaling. I am not talking too much about this method because I don't know it well enough to present to you today, but I will provide you some references that may interest you if you have some scale effects and with time dependency phenomenon.

Today, I will talk to you about the experimental approach for scale effect determination in the French sodium fast reactor. What is the purpose of my work during my Ph.D. on the MICAS mock-up?

First of all, I will present to you the general methodology when you plan to perform some experiments in order to understand the scale effects you will have.

First of all, you have to perform a dimensional analysis. This is what I already presented to you. You are using either the Vaschy-

Buckingham Theorem when you don't exactly know how does your system behave or you can use the dimensionless equation to find the similarity parameters. It is to get a general understanding on your phenomenon.

Then, what should be done is you have to perform a calibration which means you need some scale 1 prototype data, and you need to compare results on small scale mock-up with the scale 1 prototype data. If there is a deviation between your small-scale mock-up and your prototype, you can perform some correction or at least get an estimation of the scale effects you will have.

In our case, it's going to be a bit more difficult because no ASTRID data are available. That is a hard problem. We are not building the physical reactor. When you cannot have access to prototype data, what we can do is we are performing a method named the scale series. It leads to the fact that the scale series is explaining that we need three similar models at different scales. When you cannot have prototype data, you use your biggest scale as a reference scale and the deviation you can see between the downscale mock-up and your reference scale will provide you information under your quantification of the scale effects that you will have.

In our case, because during my Ph.D. we cannot build a bigger scale than MICAS that is already scale 1:6 of the ASTRID reactor, we will use this as a reference scale saying, okay, it is the biggest scale we will have. Now, what I had to do is to design two new mock-ups to be a representative of the MICAS flow and what will happen in sodium fast reactor.

Now, that we know we are going to perform the scale series techniques, let's apply the Vaschy-Buckingham Theorem. Okay. Here, it is, a schematic of what is happening. We have hot jets coming out of the core going through the porous plates and, okay, at nominal flow rates. Just a reminder, the jet is supposed to go downward but when we have a low mass flow rate, the jet will go upward as we can see here.

First of all, we list all the governing parameters. It can be either geometrical parameters such as height, for example, between the porous plate and the exit of the core, it can be some temperature, it can be the density, and it will lead to a group of dimensionless numbers. Here, using the Vaschy-Buckingham Theorem, you can see that we have nine dimensionless numbers. Some of them are geometrical such as P1 or P9. Some of them are force ratios such as P2, P3, or P4. Some of them are just about the temperature differences or also properties of the flow. You can also have some more dimensionless number, of course.

As I said, when you have more than six dimensionless parameters, this approach is strongly criticized and we cannot, just looking at this array, say, okay, this dimensionless number can be neglected and this one cannot. We will also use, of course, the governing equation. Using the dimensionless Navier-Stokes equation with some assumption, we can find while studying turbulent jets.

Because the Vaschy-Buckingham theorem is not really suitable for this, we are putting some assumption into our dimensionless Navier-Stokes equation. We are assuming a stationary flow, and we are assuming that the Boussinesq approximation is valid in our case. It leads to the fact, using the theory of turbulent jets that we have two – three, to be exact – dimensionless numbers that are coming. We have the viscosity term known as the Reynolds number and we have the buoyancy term being a mix of the Froude number and the densimetric Froude number.

This is what we can get using the dimensionless equation and we can find it back. For example, the densimetric Froude number is just P4 multiplied by P8. It is something we could have seen with the Vaschy-Buckingham Theorem but that was not explicitly written in it. This is why it was important for us to use the governing equation too.

In our case, we are making an assumption. The first thing is that the rise of the jet is owing to buoyancy effects. If we follow this assumption, it will lead to the fact that the densimetric Froude number may have strong influence and should be used as a scaling parameter at least to see if this idea can provide good results about scale effects or not. Now, our assumption will be that the densimetric Froude number will be used as a scaling parameter to go from a scale to another.

As I said, we have to design two new mock-ups now that we understand a bit more the theory we have behind the jets.

First of all, when you want to study some scale effects, it is important for you to know that you should be able to get some scale factors as far away from possible from them. If we had, for example, MICAS that is scale 1:6 and we are creating another mock-up that is scale 1:6.5, we will not create enough distortion to be able to see if we have scale effects or not.

First of all, we try to define our maximum scale. The maximum scale, in our case, is, because of material limitation, we are working on a loop that will have a maximum mass flow rate of 15 cubed meters per hour and, by applying the similarity of the densimetric Froude number, it will lead to a maximum facility size of 1:2.5. It's a problem because, of course, we want to ensure the similarity of the flow. By doing it, it will lead to 288 laminar jets. The premise, if we are doing this, we are creating a scale effect. We are creating a distortion of the physical properties of our flow.

We had to find a solution and the solution is to create a geometrical distortion in order to avoid a physical distortion. We reduced the jet number. Instead of 288 hot jets, we decided to get only 19 bigger jets. By increasing the jet diameter, we will ensure the turbulence of the flow and, of course, in order to not create too much distortion, we studied the measure of the jets to make sure that we will find an equivalent flow by having less but bigger jets in our setup. We performed this study in order to make sure that we will not create too much scale effects and avoid, let's say, a distortion on the turbulence of the flow.

Here, we can find – let's take a look at the picture on the right at first. In this zone, the fissile zone, you will have all the hot jets and you can see in green, for example, the cold jets I was talking to you at the beginning of the presentation.

On the left here, you will find the core in the MICAS mock-up with the 288 hot jets in the middle and the cold jets on the periphery in this zone and in the periphery cold zone. What we did, as I said, we increased the jet diameter. We kept the same aspect ratio, but we increased each jet diameter, we reduced the number in order to keep the turbulence of the flow. The cold jets were already laminar on the flow in MICAS. We chose to keep them as close as possible from the reality using the scale ratio while downscaling the phenomena.

Now that we have this criterion for the highest scale, we can also use the same to find the minimum scale we can have because we still have to be able to ensure the turbulence of the flow on the whole range of the study. For this, it leads to a minimum scale of the mock-up I designed of 1:4 of MICAS.

But also, distortion can be performed, sometimes not in order to avoid some effects but in order to study them. Let's take a look at what is known as the upper core structure. The upper core structure is the part just above the core. It is used for some instrumental setup in sodium fast reactor. You can see these tubes.

They are known as sheath tubes. The jets are going out of the core here. Some part of the flow will go inside, and they will go inside the upper core structure flowing through these holes, you can see, in this zone. Of course, it is leading to a loss of pressure coefficients, and we already know that it is non-linear with the velocity.

What we decided to do with the small-scale mock-up is that we chose to reproduce the zone under the upper core structure in order to keep the same flow repartition in this zone and to not provide a perturbation after the impingement of the flow repartition. But we chose to replace the part inside the upper core structure with an adjustable piston in order to be able to moderate and change the loss of pressure coefficient inside the upper core structure.

Here, the main point is, we want to create a distortion in order to see the effect of this distortion on our phenomena to make sure that, okay, does this have an influence or not and to define a validity domain for which we can say, okay, our phenomena, the rise of radial jets, is not influenced by the loss of pressure coefficient we can find under the upper core structure or maybe this is something that we will see later.

Now, I can tell you that the small-scale mock-up known as MOJIT-Eau, it will be scale 1:4 and 1:2.5 and, as I said, we are using MICAS as a reference scale, that's here. This is the whole range of the study we will be able to perform to see if we have distortion.

For example, we will be able to compare results from scale 1:4 to scale 1:2.5 and results from scale 1:2.5 to scale 1 and, of course, from scale 1:4 to scale 1 in order to see do we have scale effects, is there any distortion and, if so, we can see either the distortion and the evolution of the distortion with the scale in order to find some, at least on first approach, some transposition parameter in order to go from scale 1 MICAS to the scale 6 because, of course, ASTRID will be the scale 6.

I am showing you some pictures about the MOJIT-Eau setup scale 1:4. You can see it's a replication of the upper core structure. You can see here the porous plate. Everything is identical as we can find in MICAS except, of course, for the distortion of the hot jets, as I was saying, and you can see my hand for scale just to show you that it is a really small mock-up that is supposed to represent a whole nuclear reactor.

Now, because, as I said, we will have to compare results from a scale to another so maybe we should start to have some results and we will start with the scale 1 result we will have on the MICAS mock-up.

First of all, I am sorry, we still have to talk a bit about theory but, this time, not theory about scale effect but theory about the rise and the drop of a jet.

The rise of a jet can be defined with three parameters.

First of all, you will have the half-width L_0 for jet saying that, okay, if you had, for example, a round jet, it will be equivalent to the radius. You will have the half-width of the jet. You will have the distance of the exit of the jet to its rise or its drop depending on what you are studying. This distance, X_Z, and you will have a final angle, θ_f.

Generally, the X_Z relation is known. It is something that has been studied a lot in bibliography. I am showing you here a reference from Papakonstantis et al. It is saying that, okay, we already know the theoretical relation between this distance and the densimetric Froude number and, of course, it is related to the half-width of the jets. It is saying that, okay, this ratio is equal to the constants that only depends on the initial angle.

During our study, because this is already known, we chose to focus on the evolution of the final angle to see do we have scale effects on this final angle. For the rest of the presentation, we will adapt a convention about the jet angle, the jet final angle. At nominal mass flow rate, as I said, we have a jet that will go downward. If we have a jet that goes downward, because it is a nominal condition, we adapt a convention saying that this jet has an angle above 0, so the angle will be positive. When the jet is going upward, the angle will be negative. For example, here, we have something that is around minus 30 degrees.

Now that we have this convention, we can talk about experimental setup. In order to find some at least velocity results, we will use a method that is known as PIV. PIV stands for Particle Image Velocimetry. We are using nylon particle that would be around 4 micrometers and a 4-megapixel CCD camera. For the people who may not know what is PIV, it is a method when you put some nylon particle or it can be other particle but, in my case, it is nylon particle inside your field. This particle, because their density is very close to the fluid one, they will move with the flow.

Then, what we are doing, we are using a laser that will provide the laser sheets that will enlighten these particles. Then, perpendicular to this laser sheet, we have a camera. The camera will record, will picture two frames very close to each other and so we will see between the two frames the particle moving and because we know the time lapse between the two frames, we can define how does the particle move, we can go back too, we can find the velocity of the flow. It is a method to find the velocity of the flow. It is instantaneous result.

In my case, I am working on a stationary phenomenon, so we are averaging 150 images, which is a bit more than 10 seconds of acquisition, using a software named INSIGHT 4G in order to perform the PIV measurements.

Why are we doing PIV measurements?

It will help us find experimental results on the final angle, θ_f, which is the main point that is interesting me to see the scale effects on it. It will also provide me information about the jet half-width, L_0, and I would find the radial jet velocity.

But we also need to get some temperature measurements. For the temperature measurements, we are using PT100 probes because they have a really low uncertainty. We are using them to get the hot jets temperature, to get the environment temperature that we can get in the environment and also in the pump pit where everything is getting mixed, and we can find it in the upper core structure to make sure that we are not losing too much energy between the outside of the core and the zone. We are also using some thermocouples just to get information about the stratification and to make sure that during our experiments, we have a stabilized flow.

What is the output, of course, we are expecting from these measurements? It is to get, as I said, the jet temperature and the environment temperature in order to find the density differences we can have between hot jets and the colder environments.

Now, we have to talk a bit about the experimental condition we will apply. First of all, we keep an identical flow repartition in the core as we should have in the ASTRID reactor, which means 95% of the mass flow rate will be in the hot jets and only 5% of the mass flow rate will be in the cold jets. Because we have to define our similarity criterion, we choose to keep the densimetric Froude number, as I said before, we find with the dimensionless governing equation.

We choose to keep it at the core exits and keeping the same densimetric Froude number at the core exit should provide us, let's say, experimental conditions that are supposed to be close to the one we will have in ASTRID while studying the thermal hydraulic on this special issue. But we have to change the densimetric Froude number in order to see the dependency on our phenomenon which is the remainder of the rise of the jets. We have to study the dependency of the rise of the jet with this dimensionless number.

What we will do is that we will change the densimetric Froude number out at the core exits to see how does our system behave while the densimetric Froude number is changing. We will have experimental condition going from 20% to 100% of the nominal flow rate in ASTRID using the similarity of the densimetric Froude number and we will change the densimetric Froude number by changing the mass flow rates because we have two ways to change it. Either we change the density differences with the jet and its environment, or we change the velocity. It is way easier when you are doing experiments to only change the velocity and keep the same temperature.

Now, let's see some results.

First of all, I am just showing you four PIV results. It is images. What you are currently seeing are the velocity vectors in this zone. You have, just here, this upper core structure. We are still looking at the jets outside of the core after impingements when the 288 hot jets already merged.

What we can see, it seems that's okay. At least with our experimental range, we could capture the moments before when the jet is going downward as it should, and we can see it start to rise. Picture three and picture four, we can see it getting really high. At least, our experimental condition could ensure that we can study our phenomenon. Then, what we seem to see from picture one to three is that when we decrease the mass flow rates, we are seeing the jets going more and more upward.

But we have an issue. Between pictures three and four, we can see that the jet is going more upward or has a higher or a lower angle depending on the convention. For us, it is, let's say, a lower angle. It should be more negative even if we have a higher mass flow rate compared to the one, we have on picture three. But we also can notice that, on picture three, we have 2.1-degree differences between the jet and the environment.

In picture four, we have 4.4-degree differences. It means, when you are comparing the densimetric Froude number to the fact that while decreasing the densimetric Froude number, it seems that the jet weight is going more and more upward. It is something that we can definitely see on the four pictures. We start at densimetric Froude number of 41 with the jet going downward and, the more you decrease it, the more the final angle is getting important or less important depending on the convention. Of course, it is in negative in our case.

Let's study it a bit more.

When you get some PIV results, at first, you just have an image, you have some vectors, you have to find yourself or you can calculate your conditions. I am just showing you how I am doing it.

First of all, I developed a Python code to define a window in this zone and you are using the theory of turbulent jets saying that the maximum velocity you can find in the jet is in the center of the jet. By putting only the maximum velocity on the final angle of the jets, you can find kind of the jet angle by just doing a linear regression in this zone. It is helping us to get an approximation of the final angle. What we also need is we define another window because we still need the half-width of the jets. In this window, we decided to plot all the velocity vectors.

As you can find here, we can find kind of the same profile as we should find in theory saying that a hot turbulent jet has a Gaussian profile and we define a criterion saying that, okay, we say that a velocity vector belongs to the jet only if it is above 10% of the maximum velocity because else we get some vectors, for example, that are not really in the jets because the flow is still moving a bit around.

Then, once we get it, we have the radial velocity, we have the half-widths, we have the angle, we can define a radial jet densimetric Froude number which is equivalent of saying, okay, let's say we did not really have 288 hot jets. What would have happened about the physics if it was just one radial jet? We have one jet diffusing into a colder environment. This jet would have had an initial densimetric Froude number that we can calculate this way using as the experimental velocity in this zone that is calculated as you can see here and you can keep, of course, the difference of density between the jets and the environment and you can use then the half-width of the jet L_0 that we experimentally found.

Once we define this radial jet velocity, you can keep going with the study. It is what is plotting here in blue. In blue, it is the evolution of the angle of the jet, the final angle of the jets, with the densimetric Froude number calculated after impingements, as I showed just before.

In this zone, what we can see is that it seems that we have a linear evolution of the angle with the densimetric Froude number. What will be interesting for us for the rest of the study is to use the critical densimetric Froude number that we define as the value of the densimetric Froude number for which our jet is going from a downward jet to an upward jet which means it is value for which θ_f is equal to zero. It is important for us to know it, to compare it from a scale to another. Then, this is what we have for an upper if we were just using one radial jet.

In our system, the physics is a bit more complex. We have 288 hot jets. What we are doing and what we did, in fact, is that we applied the similarity of the densimetric Froude number not in this zone here, but we applied it at the core exits. We are doing the same as previously. We are plotting the evolution of the final angle with the initial densimetric Froude number. Initial meaning that it is calculating at the outside of the core.

It seems that we have the same kind of evolution. We still have one linear zone of the evolution of the final angle with the densimetric Froude number and then we have an austenitic zone that we have on both ways. It is the angle we get when we have a high densimetric Froude number which means a really high inertia, low buoyancy effects. It is the angle you can see here when the jet is going downward. It is an angle around 20 degrees.

First of all, maybe some of you may have noticed between the plotting in orange and the plotting in blue, it seems that we have a similar behavior. It is not something that was obvious because while calculating the jet outside of the core they are going through non-linear phenomenon but, if the mass is going through the sheath tube and going inside the upper core structure, we have loss of pressure because of the porous plate and we are losing energy because of the impingement. It was not something obvious that we could find the exact same behavior. What is really changing is the value of the densimetric Froude number we have in these two zones.

We are trying to study the effects, for example, of what is happening if we wanted to find a relation between what is happening outside of the core and what is happening in this zone. For this, we choose to normalize our results. The normalization is made by the nominal densimetric Froude number that we should have at nominal condition saying that, okay, when you have a densimetric Froude number normalized equal to 1, it means it is what should happen when you have 100% of your nominal mass flow rate in your mock-up using the densimetric Froude number similarity. You have the definition just here.

What is happening is that we can see the two curves are really close to be the same. It leads to our first preliminary conclusion that maybe we have no real influence of the non-linear phenomenon under the upper core structure, so above the sheath tube and the porous plate. It seems that all the non-linear phenomena happening in this zone may be completely negligible when you are studying the effects of the rise of the jets. It leads to another conclusion that maybe, after normalization, we could say that 288 impinging jets can be studied as one free radial jet.

Why is it really interesting for us is that because you don't have a lot of bibliography about the thermal-hydraulic behavior of 288 hot impinging jets in the literature but one free radial jet in a colder environment, you have a lot of documentation about it. We still have to find the exact transformation from the core exit to the radial jet, but it seems that, with the normalization, we can get really close results and maybe simplify our study.

The next step. Because, of course, this is all we have with the MICAS' result, but we need other result to compare from a scale to another when we are performing some scale effects.

First of all, we are using another mock-up named PIGNIA to get a better understanding on exactly what I said which means how can we understand what is happening after impingement and find a relation between the densimetric Froude number after impingement and the densimetric Froude number at the core exit.

The PIGNIA setup is an oversimplification of the MICAS mock-up and the MOJIT-Eau mock-up. It is just a one single jet. You can see the single jet here impinging a flat plate. We have no geometrical representativity. We have really no scale representativity. It is more an oversimplification in order to study – the question we are trying to answer is – will the jet angle get the same evolution and the same critical value as we get in MICAS while we are just studying one impinging jet.

The phenomenology we are studying is the evolution, of course, of the angle with the densimetric Froude number. We are also trying to evaluate some distortion we could have by changing, for example, the H divided by D ratio because we can change the distance you can have between the jets and the impinged plates. Our main point is still to find a theoretical and experimental relation between the jet exits and the radial jets in order to try to apply this to MICAS then to say, okay, if we are studying one free radial jet, we can say that, in our reactor, it will behave like this because we know how to transpose results from this zone to this zone.

Now, let me show you some experimental results we already get on the PIGNIA setup. There are preliminary PIV results. You can see that, okay, from the left to the right, we have decreasing mass flow rates – increasing, sorry, mass flow rates. You can see that the more you increase, of course, the mass flow rate, the less buoyancy effects will be important so the more your jet will go downward.

First of all, we can already see that when you really have a lot of inertia for really high densimetric Froude number, I cannot show you exactly the value yet because we are still calculating some. These are some experiments that we performed two weeks ago. I still don't have time to analyze everything, but we can already tell you that we have one geometrical influence because when you have a high densimetric Froude number.

In the MICAS mock-up, we could see that the jet was going downward. On the PIGNIA setup, you can definitely see that jet is not going upward. It is staying at the 0-degree level. It's already provided us some information about geometrical instruments you can have because, on MICAS, maybe this is something I did not really show, but you have some part here that may have an influence on the flow. With this mock-up, we already showed that it has an influence on the flow, so maybe with the MOJIT-Eau mock-up, we could show that decreasing this distance too may be important for the jet angle.

Now, what is happening with the MOJIT-Eau mock-up?

The experimental campaign incoming. I am sorry. I cannot show you right now results to compare with the upper scale MICAS. The experimental campaign is coming and what will be compared with the MICAS results are the critical densimetric Froude number. Just to remind you, it is the densimetric Froude number for which we will have a final angle equal to 0 degree. It is this zone.

We will also compare the slope of the evolution of the angle. This slope, we can have from a scale to another to see if the system is really behaving the same and we will try to find also do we have a constant angle for high densimetric Froude number. For example, on the MICAS mock-up, we have an angle of 120 degrees. Maybe on MOJIT-Eau, we could have something that will be 10 degrees or maybe 30 degrees. We don't know yet. If we have differences, it will be directly scale effects.

As a conclusion, first of all, the question is how can we conclude. As I said, it is still an ongoing study. I am really sorry. I cannot provide you all the conclusion right now. We still have to wait a little bit. If we have no scale effects, what will happen is that we should be able to find identical results between MICAS and the lower scale MOJIT-Eau. When I say identical results, I am saying we have exactly the same critical densimetric Froude number for which the final angle is equal to zero, we will find the exact same slope of the evolution of the final angle with the densimetric Froude number, and we will find the same constant angle when we have a high densimetric Froude number.

In that case and only in that case, we will be able to conclude that the conservation of the densimetric Froude number ensured the similarity of the flow and so we could be able to conclude that we have no scale effects if the densimetric Froude number is kept at the core exit from a scale to another. But there is low probability that it happens. Maybe? Who knows? But if we have some differences because we have to anticipate that kind of results.

If we have just one difference on one of these items, just on the critical or maybe on the flow, on the slope of the evolution of the angle – if we have just one difference on an item, what will happen next is that you have to study how does the differences evolve with the scale factor. Maybe it is something linear. Maybe you have an angle that is, okay, when you multiply by two the size, maybe the angle is multiplied by two, then you will be able to find something to still transpose your result because you will be able find a relation between your phenomena and your scale factor.

Then, what you can also do is to study how does the differences you find from a scale to another – how does the differences evolve with other dimensionless number. You can perform some experiments by changing the Reynolds numbers, the area number. You can try to find, okay, what are the force ratio that we thought were negligible but, in fact, were not. In that case, anyway, what, as a first conclusion, we will be able to draw is that the conservation of the densimetric Froude number only is not enough to ensure the similarity of the flow.

Now, as a conclusion of this webinar, I can just say that keep in mind that all experiments on small scale mock-up may lead to scale effects compared to a prototype. You have a lot of ways to avoid scale effects or at least study them. You have some complex approach for everything that is transient or two-phase flow phenomena. This is what happened a lot if you do some bibliography about the loss of coolant accidents for example in PWR.

You have different scaling techniques for Integral Effect Tests. You can perform some calibration with scale 1 results. But then, when you have to perform yourself a scale effect analysis, you have the dimensional analysis and scale series to find, experimentally, the scale effects, you will have between a mock-up and experiments and then to be able to validate the simulation code you are using.

On this phenomenon, to conclude this webinar, as the ongoing study are about the scale series, we have some ongoing studies with the scale series using MICAS as a reference scale and a scale of 1:2.5 and 1:4, the MOJIT-Eau mock-up.

Right now, we already could be able to show a dependency of the jet angle with the densimetric Froude number so it showed that at least the densimetric Froude number will be important in our study. Maybe it is not enough but the first experimental result showed that it is an important criterion to keep from a scale to another.

Now, we are just doing some phenomenological study on oversimplified mock-up, the PIGNIA mockup, in order to have a better understanding of this phenomenon before going on experimental campaign in the MOJIT-Eau mock-up. As I say, it is still an ongoing study.

The final conclusion of the scale effect on the phenomenon in French sodium fast reactor, it should be known within a year, when I will complete my Ph.D. If you have been interested in this webinar, and I am sure you have been interested in this webinar, you can keep my contact and look after my next publication and then we will have the conclusion about the scale effects analysis we can perform in sodium fast reactor.

Now, I am showing you some references that may be interesting, especially if you have some really complex flow. I can tell you that these two references, the book, Design-Basis Accident Analysis Methods for Light-Water Nuclear Power Plants and as a report for the Nuclear Energy Agency, they are showing another view on all the scale effects and scaling techniques we can find in the nuclear field.

Now, I just would like to thank everyone. First of all, thanks to the Gen IV International Forum to make this possible and thank all the listeners that were here and, if you have any question, we can discuss it now. Thank you very much.

Berta Oates
Thank you, Benjamin. Thank you very much. I am sure that we do find your presentation very interesting.

While questions are coming in, let's take a quick look at the upcoming webinar presentations.

In April, a presentation on the GIF/IAEA joint webinar. It will be a panel discussion on the Role of Nuclear Energy in Reducing CO2 Emissions, which promises to be a very enlightening presentation, and all are welcome to join.

In May, Development of Nanosized Carbide Dispersed Advanced Radiation Resistant Austenitic Stainless Steel, or otherwise known as ARES, for Generation IV Systems.

In June, a presentation on the Nuclear Waste Management Strategy for Molten Salt Reactor Systems.

If you have questions, go ahead, and put those in the question pane. The only question that I see thus far is where is the link to the presentation and there is a handout pane either in your control panel or if you are on a mobile device, along the top. Usually, it's along the top of your mobile device, maybe along the margin of your device. There's a pane to download that PDF. If you still have difficulty, just shoot me an email and I will send you a copy. It will be uploaded to the GIF website along with the recording from today's presentation. Again, just give us a couple of days to get the webmaster the information and get that upload completed.

Benjamin Jourdy
It seems that the presentation was really clear as there is still no question.

Berta Oates
I don't see any questions coming in. Congratulations again for your presentation in the competition in pitching your Ph.D. I think that the workforce has such promise in this next generation. I am just thrilled to see the work that you will have in your future, Benjamin, and I wish you the best of luck. I think that you are going to make a huge impact and you are just exactly what the nuclear industry needs.

Benjamin Jourdy
Thank you very much. It means a lot for me. Thank you very much.

Patricia Paviet
Yes, I echo the same, Benjamin. Thank you so much for your presentation and I know you are doing your Ph.D. and you talked one hour, so congratulations. That's an exercise and we wish you all the best.

For the audience, if you have any questions, it was very technical. You have the email address on one of the slides so do not hesitate to contact Benjamin.

Berta Oates
Thank you, everyone. Have a great day.

Patricia Paviet
Okay. Thank you, everyone. Bye-bye. Bye, Benjamin.

Benjamin Jourdy
Thank you. Thank you very much. Have a great day. Goodbye.

END