Security Study of Sodium-Gas Heat Exchangers in Frame of Sodium-cooled Fast Reactors
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Her Ph.D. research aims at providing a numerical tool that enables users to describe the structure of the jet as a function of the flow rate of the gas leak. The developed model is implemented in CANOP, which enables users to generate the Adaptive Mesh Refinement and to calculate in parallel.

So without any further ado, Ms. Chen, I will give you the floor. Thank you again for this webinar presentation.

Fang Chen
Okay. Hello, everyone. First, thank you for this short introduction of me and thank you, everyone, who came to listen to my talk. I want to add one more information about myself. My Ph.D. defense will take place on the 2nd of October and you are welcome to attend my Ph.D. defense as well.

During this 3-year Ph.D. research, I worked on the modeling of compressible multiphase flow. And today, I am going to talk about my research application in SFR, security study of sodium-gas heat exchangers in frame of sodium-cooled fast reactor.

I'll begin my talk by introducing the context and the objective of present work including ASTRID project and its innovative concept SGHE design. Then I am going to highlight the development of present work such as predominant physical phenomenon, mathematical model for multiphase flow, and its numerical measures, etcetera. I'll continue by briefly discussing some results in part three including validation tests and the application of under-expanded gas jets modeling. Finally, I'll finish my talk by the conclusion and perspectives.

Now, let us start with the introduction of the ASTRID project. French nuclear policy towards a more sustainable nuclear energy, the closed field circle, it requires a circle based on fast neutron reactor. French fast reactor program priority is given to the SFR, well, the ASTRID project. The main objective of the ASTRID project is to provide a demonstration on the operability of SFR industrial reactors. So as SFR or we say ASTRID type reactor, the main favorable features are: first, the whole primary loop is contained in the main vessel including the core and the primary pumps, etcetera. Second, the good properties of sodium such as a large boiling margin, for example, at a pressure of 1 bar, the temperature from around 100 to 900 Celsius, the sodium remains in liquid phase. Third, SFR has a high thermal inertia in case of loss of main heat sink due to the large quantity of primary coolant. And besides, there is no xenon effect, no need of soluble neutron poison.

And collective dose on a pool type SFR is very low compared to PWR. Here, the feature that I want to emphasize for the present work is the intermediate system provides an extra containment between the primary loop and the environment. It avoids any radioactive material derived [ph] from the primary vessel.

The intermediate heat exchange transfer of the thermal power from the primary loop to the third one, which is the Power Conversion System, PCS.

In the frame of PCS, a study for ASTRID reactor, in order to improve the safety especially sodium-water reactor risk, there are two systems started in parallel. First, the classic one is water steam PCS with steam generator. The objective of this system is to improve the robustness of steam generator relative to the sodium-water reaction and the sodium-water reaction knowledge and its modeling etcetera.

The question is how to minimize the sodium-water reaction risk in SFR. This question leads to the study of another concept, the Gas PCS. In [Unclear] circle, gas power conversion system, sodium gas heat exchanger, SGHE, using the initial gas replaces the steam generator. And it is CEA in charge of this in its development. And this is also one of the main innovative option in investigation for ASTRID project and our present work is in the frame of the SGHE development.

This development requires different fields of studies. First, the components [Unclear] on three disciplines in strong interactions. First one is general design. The general design study which proposed a three-dimensional view taking into account the technical constraints. The second one is the thermohydraulics. It runs to divide heat transfer surface taking into account the efficiency and the heat exchanger technology. The last one is the thermomechanical analysis. It allows justifying the design. At least the design process is iterative and it's coupled with resources and developments of materials and physical chemistry. So constraints [ph] from regulatory aspects and with use of sodium should be also considered.

Finally, both the design and manufacturing should be validated through a number of phases at different scales before proposing SGHE in its final version.

The general design of SGHE is shown on this slide. The SGHE concept is a component power unit of 180 megawatts thermal. It means two components each and secondary sodium loop. The principle of this design of SGHE is based on a component integrating eight elementary modules of compact heat exchanger into a pressurized vessel which also plays the role of inlet manifold. This design options [Unclear] maximizing the compactness [ph] and minimizing the pressure drop, minimizing the sodium inventory in the components, and limiting those more mechanical stresses, etcetera. And a test of 40 kilowatts SGHE was carried out in CEA and the efficiency can reach up more than 37%.

In this design, what I want to emphasize is the nitrogen is chosen for the tertiary loop and the pressure of nitrogen is 180 bars and, well, the liquid sodium is 5 bars. So in an accident scenario where the heat exchanger wall cracked, this huge pressure difference across the wall could lead to a gas leak submerged into liquid sodium. And quoting the previous studies in CEA, the gas leakage can be classified into several types by the crack size. One is a supersonic jet noted, under-expanded gas jets. This is the one who covers all physical phenomena of different gas leaks. So, particularly in safety analysis, the structure of under-expanded gas jet enables to develop the acoustic method to detect these gas leaks, for example, based on the bubble distributions and Mach disk.

What is the Mach disk? As we can see, this is the picture of the general structure of an under-expanded gas jet submerged into a liquid. And as we can see here, this is the Mach disk which separates the floor into regions, supersonic region, upstream of jets, and subsonic region, downstream of jets.

Let's come back to the safety analysis. The acoustic methods requires a dedicated knowledge of jet structure. So in order to achieve this study at a different physical phenomenon, the CEA carried out a number of collaborations with the other research institutes and centers. For example, at the point of viscous effect inside of nozzle flow, we have collaborated with the IMFT in Toulouse, France. For the study of compressible flow, particularly for the barrel shock and Mach disk, we did work with IMFT, IUSTI in Marseille France, ANL, and in USA. And for the acoustic detection for leak noise, we have collaborated with KTH. Liquid droplets behaviors in supersonic flow, we have worked with IUSTI. They did experiments for the CEA. Concerning the bubble distribution study, the experiments of nitrogen gas injected into water and liquid sodium were carried out on SNAKE facility at ANL. As we can see, this is the photo of SNAKE facility at ANL. In the frame of this work organization, the objective of present work is to provide a numerical tool to estimate the structure of under-expanded gas jets as a function of flow rate of gas leak.

Next, I'd like to talk about the development of present work in detail starting by development process. First, we started the development process with the identification of the physical phenomena and it allows developing a mathematical model to describe this physical phenomenon and then we implemented this model into a numerical tool and carried out several validation tests to verify our mathematical model.

Once the model and numerical schemes are validated, we applied the code into the under-expanded gas jet modeling and compared the results with the reference cases. And this process tracked the agreement between the developed model and the identified physical phenomenon. So some improvements could be done accordingly.

Concerning the identification of main physical phenomenon, the velocity inhomogeneity between two phases is started firstly. First, carried out experiments of nitrogen injected into water with a stagnation pressure of 20 bars and the nozzle diameter of 0.7 millimeter. And the results showed that the velocity difference between two phases could reach up certain hundred meters per second.

Besides, a previous Ph.D. work of Vivaldi in CEA carried out a numerical study of gas injection into a sodium liquid with a stagnation pressure of 7 bar. And it shows the similar velocity difference as well. So this viscous inhomogeneity should not be ignored in our case. So our model needs to consider the velocity of each phase and the momentum exchange between both of them while integrating the drag force between continuous phases and dispersed phases.

In an under-expanded gas jets submerged into a liquid, as we talked previously there are dispersed phases region, bubbles, droplets, and their transition. The evolution of bubble size depends on the pressure difference between the inside and outside of the particle. As one objective of present work is to track the evolution of dispersed phases, bubble size evolution. The model needs to take into account the pressure inhomogeneity as well.

As to viscosities, we did a numerical study of monophasic under-expanded gas jet in an SGHE channel. And this work was published last year. It's shown that the viscous effect inside of nozzle influences the structure of downstream of jets. For example, the curvature of the incident shock waves, particularly the Taylor-Gōrtler vortices due to the comparison between the centrifugal effects and viscous effects in the boundary layer are observed.

As we can see on the bottom picture, each impact produced by the under-expanded gas jets corresponds to counterrotating vortex pair. And these vortex pairs are from the Taylor-Gōrtler instability; therefore, it's very important to take into account the viscous diffusion in the pure phase in our model.

Except these three predominant physical phenomena, we have checked that there is no chemical reaction according to the experiments carried out at ANL. Ad, besides, there is no phase change in under-expanded nitrogen jet into liquid sodium.

This picture, we interpolated the state points into the phase diagram of nitrogen, sodium, and water. They are, respectively, in the purple, blue, and orange color. These state points are obtained from the numerical study of monophasic jets in an SGHE channel. And from this, we can conclude that under the SGHE operation condition, there is no phase change of nitrogen and sodium. Meanwhile, for the nitrogen into the water, there could be a phase change of water.

According to the previous study of physical phenomena in nitrogen jets submerged into sodium, we developed our mathematical model from the Baer-Nunziato model which enables to model two velocities and two pressures. And the systems include momentum exchange via integrating the drag force between two phases and the viscous effect in the pure phase. Numerically, the agreement [ph] problem for biphasic flow is solved by Rusanov solver and the model is interpreted into a MUSCL-Hancock scheme. Until now, the question is, is there any other systems that we need to consider.

First, I want to show you a very interesting biphasic shock tube test. As we can see in this picture, in the shock tube in the left chamber is filled by a gas with a pressure of 180 bar and the right side is filled by liquid sodium with a pressure of 5 bar. And this is the same condition with the SGHE operation condition. The equation of state is Albert-Nobel-Stiffened-Gas for both of them.

First, let's see the results. This is the profile of velocity. In the right side of the shock tube where the gas is absent, the velocity of gas noted fluid 2 reached about 1000 meters each second. The same result is observed in the pressure profile. For example, on the right side of the shock tube where the liquid phase noted fluid 1 is absent, and there is a huge change in non-physical of pressure. And this observation is noted in physical. Therefore, we need to add something to correct these non-physical effects of the fictitious phases in the pure phase.

The solution that we find is the velocity and the pressure relaxations into the model. And this is the result obtained with the model adding the velocity and the pressure relaxations. We can see that the non-physical effect is corrected.

For the next stop, numerically for the under-expanded gas jet modeling, in the dispersed phases and shock wave regions, we need the mesh well refined. And in the other regions, we don't need the mesh be refined like this. So a numerical tool which enables to generate adaptive mesh refinement fits our need. So, we interpreted our model into a numerical tool named CANOP. There are two layers in CANOP. The low level layer enables to carry out a cell-based adaptive mesh refinement and computation in parallel by integrating the P4est library. As we can see, this is an example of AMR generated by the present code and it's controlled by the density gradient. It means that mesh is well refined in the way that the density gradient is very strong. In the high level layer, it enables us to implement the numerical schemes with the finite volume method particularly for solving the problem in the fluid dynamics field.

In more detail, the common functions in CANOP are in charge of the time iteration, mesh adaptation, quadrant management, connectivity, etcetera. Based on these common functions, we can develop branches for each problem by defining the user data, numerical schemes, boundary conditions, initial conditions, etcetera. The present work develops a new branch to solve the problem of compressible multiphase flow, particularly for the application of under-expanded gas jets into a containment channel named superbifluids. And then we can send our tasks to IDRIS machine. This is Institute for Development and Resources in Intensive Scientific Computing which enables to launch the intensive computing.

Now, let's move on and discuss results including model validation and its application of modeling of under-expanded gas jets.

There are three steps in the calculation strategy. First, we focused on the validation of convective part by the two-phase shock tube test, and then validation concerns of source terms including viscous diffusion in pure phase and the momentum exchange between the continual phases and the dispersed phases. Once the validation is finished, we applied the model to carry out the modeling of under-expanded gas jets.

At the point of convective part validation, I'd like to show you an example of multiphase flow shock tube test. The initial condition for the fluid 1 are identical for the two chambers accepting the volume fraction. In the left chamber, it is 0.7. In the right chamber, it's 0.3. For the fluid 2, the high pressure is located in the right chamber. It means that the shockwaves will propagate from the right side to the left side.

This is the comparison between this exact solution and the numerical results of fluid 1. The discontinuous initial condition of fluid 2 causes shockwaves and expansions for the fluid 1. And besides, we can see that the numerical results agree well with the exact solution.

For the fluid 2, the shock waves propagate to the left side. And we can see the contact surface and volume for action contact surface are well produced by comparing with the exact solution. In conclusion for this part, according to a number of validation testers, we can conclude that the convective part is validated.

For the viscous effect validation, we did a classical test, Poiseuille flow. The gas flow enters from left inlet into a channel of 0,2 measure. Here are the numerical results compared with the exact solution. I want to explain here the key noted L, for example, 3-8 means that the minimum and maximum level of AMR is 3 and 8, respectively. And we can see as well the numerical results agree well with the exact solution. It allows us to check the integration of viscous effect.

Now, let’s focus on the momentum exchange. At this point, we did the test with a gas-water mixture that the velocity of each phase is different. The figure on bottom on this slide shows the velocity and the pressure evolution over time. The momentum exchange in between two phases make the velocity tend to be same over time and the new pressure profile for each phase. As a conclusion, the system of momentum exchange is validated.

Overall, the developed model and its numerical scheme are validated. So in the following slide, they are applied into the modeling of under-expanded gas jets.

First, I want to show you one comparison with the experiment. In this study, the nitrogen of 180 bar was injected into water of ambient pressure. And this is the generation of gas jets over time. And comparing with the experiments, the jet is in a mushroom shape during the generation phase and vortex behind front surface of jets are well produced. These phenomenon were observed both in experiments and in numerical results.

Let’s compare the results in more details. First, I want to present the main character in an under-expanded gas jets Mach disk. In the picture at the left side, the picture noted A is obtained from the monophasic jet. The picture noted B is obtained from the biphasic jet. A very interesting difference of Mach disk between the two cases is observed. In the biphasic jet, several shock cells are produced instead of one only shock cell in monophasic jets. One reason is because the gas with very high velocity injected into liquids which is at rest and it causes the entailment of liquid [Unclear] gas. And this part will liquid doesn’t participate into the formation of Mach disk. And that is why the Mach disk of biphasic case is separated into several cells.

In addition, we compared the volume fraction results with the experiments. We can say there is a difference between both of them in bubble region here. It means the volume fraction is close to 1. Because this is the free gas jet, in this case the turbulence effect in bubble region becomes more significant. Meanwhile, the present work doesn't integrate the turbulence model into consideration because our final objective is to model gas jets in a channel with a width of only 3 millimeters.

The effect of turbulence can be ignored in such a small channel. So [Unclear] of this difference, this test shows the capability of the code to reproduce the main structure of biphasic under-expanded gas jets. It allows us to apply the code to model of the gas leak in an SGHE channel.

For this modeling, the nitrogen jet is injected into a sodium channel from a reservoir, the initial conditions are obtained from the general SGHE design. The width of the sodium channel is 3 millimeters and the crack size in this case is 0.5 millimeter. In this study, some hypotheses are considered. First, the size of each dispersed phase is supposed to be uniform. Second, the fragmentation of dispersed phases owning to the shock waves and its refracted waves is ignored. The third one, the interface properties are considered homogeneous in whole region. I will explain more at this point. In the present work, there are [Unclear] relevant to the velocity and pressure of this phase to phase interfaces.

However, in our case, there are two types of dispersed phases, bubbles and droplets. The interface properties depend on type of dispersed phase actually. But in the present work, we supposed that the interface properties are identical in the whole region. And the last one, we don't take the turbulence model into consideration.

Let's see some results. First, this is the velocity profile of gas in function of injection direction and the profile is compared with the monophasic one. For the monophasic jets, the straight discontinuity of velocity profile stands for the Mach disk localization. Meanwhile, the Mach disk localization for biphasic jet is not so straight as the one of monophasic because the flow is a mixture of gas and liquid sodium downstream of jet. And the gas liquid mixture makes the sound speed profile more smoother.

It provokes the propagation of shockwaves smoother and this is why the localization of Mach disk is smoother for the biphasic jets in SGHE channel.

Besides, as we can see here, the flow behavior near to the nozzle – here is the nozzle- is in S shape. This is due to the strong channel containment. And this containment creates the vortex near to the nozzle outline. And the flow behavior leads to the volume fraction distribution. The bubbles are advected throughout the channel and it means that it's possible to provide the data for acoustic method development based on the bubble distribution and the following work is to carry out modeling of under-expanded gas jets with different nozzle sizes in order to study the jet structure in function of gas flow rates.

On the other hand, the future validating experiments will all be performed on IKHAR 2 facility in CEA Cadarache following the present work.

Finally, let's review some key points from the present work. As conclusion, first, a biphasic flow model integrating main physical phenomenon of an under-expanded gas jet is developed. Our model enables to model each velocity and pressure for each phase, model the momentum exchange between two phases, and viscous effect in pure phase. We add also velocity and pressure corrections of the fictitious phase. Second, the model is implemented into a numerical tool, CANOP, and its capability to reproduce different two-phase flow configurations is validated. And the results of modeling of under-expanded gas jets in SGHE channel are promising.

The achievement of this work enables to schedule following work. So at the point of perspective, first, in order to improve our mathematical or numeric model, first, we can take into account the interface property in function of different dispersed phases, droplets and bubbles. And second, we can take into account the size inhomogeneity of dispersed phases as well. And experimentally, experiment IKHAR 2 will be carried out to check the flow behavior in a channel. And the experiment of gas jets in a SGHE collector may be carried out in the future.

That's all of my talk and thank you for your attention.

Berta Oates
Thank you very much. If you do have questions, go ahead and type those into the Q&A pane at this time. While those questions are coming in, we'll go ahead and take a look at the upcoming webinar presentations. In August, a presentation on Lead Containing Mainly Isotope 208: New Reflector for Improving Safety of Fast Nuclear Reactors. In September, a presentation of the Gen-4 Coolants Quality Control; and in October, Passive Decay Heat Removal System.

Does anyone have questions? If you do, you can go ahead and type those into the Q&A pane now. As a reminder, today's webinar presentation is a volunteer communication event. Thank you for those who sent your selfies. If you still want to participate and haven't sent a selfie, take a picture of yourself with the presentation in the background and e-mail that to boates@highdesertcs.com and we'll collate those pictures into a mosaic and post this on the GIF website.

Are there any questions?

Fang Chen
Okay. I don't see the Q&A pane. Is there some problem?

Berta Oates
Here we go. There's a question that asks what does the size of the droplet [ph] influence the results.

Fang Chen
Excuse me, I didn't hear you very clearly. Could you please repeat your question?

Berta Oates
Sure. There's a question that says what does the size of the droplet [ph] influence the results. I'm going to –

Fang Chen
Your question is concerning the comparison between the experiments and the numerical results, right?

Berta Oates
Do you see it now?

Fang Chen
Yeah, I see that. Yes, I see the question. Okay. Actually, the [Unclear] is obtained from the monophasic case in an SGHE channel and we compared our biphasic results with the experiments. And now, at present work, we considered the size of dispersed phase is uniform. It means we considered all the bubbles has one size and all the droplets have one size. So it means we didn't consider that the influence of fragmentation of the dispersed phases only shock tubes enter is refracted shock waves from the containment of channel. So for the results of free jet, as we can see that the result compared with the experiments carried out by Colleoc, we have a difference in the bubble regions. Well, in this region the surface tension is more significant. It means we need to take into consideration non-uniform size of dispersed phases.

Berta Oates
Thank you.

Fang Chen
For the next step, we will take these phenomenon into consideration.

Berta Oates
Do you have any information that you can share on the progress of the ASTRID project?

Fang Chen
I am sorry. I'm looking – I am reading the question on the Q&A pod. So can I answer this question firstly?

Berta Oates
Sure.

Fang Chen
Okay. Could you share on some progress of the ASTRID project? This is a very interesting question concerning the development of ASTRID project. What I know is at first, according to the French Energy policy, we start the project ASTRID in order to demonstrate SFR industrial reactor. And at the beginning, the power of design is 1500 megawatts thermal. And then, according to the change of policy, the new ASTRID is proposed and the power is reduced to 4000 megawatt thermal. And, now we say it's more than a program of development of SFR. And because of that, as I am a Ph.D. student in CEA so I focused on rather science than the project development. So maybe I can answer this question in detail by email, so send me an email.

Berta Oates
How was the pressure for the nitrogen established? Does your work suggest any modification to this pressure or the sodium pressure?

Fang Chen
This design is including multi-studies in different fields and the main objective for the pressure design is to minimize the drop loss on gas system. And I think there was a Ph.D. study concerning this research. And I think it's compared – I can't remember really clearly but it compares the operation efficiency and the material constructs and manufacturing process and so on. They fixed the pressure for SGHE of 180 bar. And at this point we can avoid saving about 20% of pressure loop of the current heater transfer zone. And I think if the pressure is more than 180 bar and the efficiency increases not very evidently, so this is the best function point.

No, I am sorry. I didn't work on the study of the design of the pressure of sodium gas heat exchanger. I just did the modeling of gas jet into a sodium channel according to the general design of SGHE. So concerning this question, modification to this pressure or the sodium pressure, maybe I can ask my colleagues and respond to you in detail by email later.

Berta Oates

Thank you. I think we got the questions and the comments that are there answered. The webinar recording of today's presentation and the slide deck will be posted on the GIF website. If you'll just give us a few days to get that uploaded, we appreciate your patience.

I don't see another new question coming in.

Fang Chen
Me either.

Berta Oates
Again, I want to thank you for your efforts in putting this presentation together and taking the time to present today. It is really greatly appreciated. And thanks to everyone who did attend and I have received several selfies so I appreciate that as well.

Patricia Paviet
Yeah. I would like to add thank you so much, Fang, for the good presentation and I wish you all the best for your Ph.D. defense in October.

Fang Chen
Thank you. Thank you, everybody

Patricia Paviet
Okay. So I guess we can finish the session, Berta.

Berta Oates
I think that's it. Yeah, I think we can conclude. There's one question here. Your results appear to be strongly dependent on the pressure difference. Can you specify the regime and the validity of your results?

Fang Chen
In order to the validation, first, we focused on the main structure of an under-expanded gas jet. It means the Mach disk that I talked much previously. And, in this case, I showed you this Mach disk distribution. And we compared these characters of Mach disk with the experimental correlations and it shows a good agreement of the Mach disk diameter.

And then we focused as well of the flow behavior in the channel at the moment. For example, as we can see, there is a [Unclear] near to the nozzle inlet and the flow behavior is in an S form. Besides, we tracked as well the velocity and pressure and the other profiles in the channel compared with the experiments and the previous study of monophasic jets. And why we did which was the pressure difference of 180 bar and 5 bars and 1 bar for the free jet. This is a reference to the experiments and SGHE channel design.

Berta Oates
Interesting. The question is why the title is security study and not safety study. Would you explain a little bit?

Fang Chen
I think I confuse with security and safety study. In fact it is more of a safety study than a security study. I agree with you. So I think maybe I made a mistake with the security and the safety study.

Berta Oates
Just a difference in language there is all.

Fang Chen
Yeah. I am a little confused I think.

Berta Oates
Does your model work as the nitrogen system depressurizes and the sodium pressurizes or is your model only producing steady state results?

Fang Chen
Yes. In inhomogeneity region, nitrogen and sodium are full compressible, both of them are compressible. It means nitrogen and sodium liquid are considered as compressible fluids, both of them. And our model produced steady state results and as well the unsteady state results over time. Not only in a steady state results. As just like I showed you, the generation phase of gas jets compared with the experiments over time. And the steady state results that you saw in the slides at the end of the presentation, the steady state is obtained by the average over time, we say.

Berta Oates
Thank you. Again, thanks, everyone, for your participation today. And with that, I think we will conclude today's presentation and wish you all farewell. Thank you, again, Fang. It was a very interesting presentation.

Fang Chen
Thank you. Thank you, everyone.

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