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Simcenter STAR-CCM+

Using CFD to improve the dependability of nuclear power plants

Executive summary
This white paper discusses how computational fluid dynamics (CFD) can be used to improve the reliability of equipment and piping for nuclear power plants, and understand supersonic-steam-jet phenomena, which occurs when pipes rupture.

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Introduction

Hitachi, Ltd. (Hitachi) and Hitachi-GE Nuclear Energy, Ltd. (HGNE) plan to build nuclear power stations that are scheduled to go into operation overseas starting in 2020. HGNE has worked with the Central Research Institute of Electric Power Industry (CRIEPI), a Japanese nonprofit foundation that conducts research and development (R&D) into technologies in a variety of scientific and technical fields related to the electric power industry, to improve the safety and reliability of advanced boiling water reactors (ABWRs) scheduled for construction, and explain the supersonic-steam-jet phenomena that might occur in case of pipe ruptures. HGNE and CRIEPI relied on computer simulations during the development process, and Siemens Digital Industries Software's Simcenter STAR-CCM+™ software, part of the Simcenter™ portfolio, was used for supersonic-steam-jet CFD.

Hitachi was founded more than a century ago, and produced Japan's first five-horsepower induction motor in 1910. Today it has 10 divisions, including information and telecommunications systems, social infrastructure and industrial systems, electronic systems and equipment, construction machinery, highly functional materials and components, automotive systems, smart life and ecofriendly systems, financial services and power systems. With sales of around $100 billion and about 340,000 employees, it is one of Japan's leading electrical equipment companies and a multinational corporation that has worldwide manufacturing and sales bases. Hitachi designs and develops a diverse range of products, including everything from appliances to rolling stock, construction machinery and energy-sector products, and Siemens' Simcenter STAR-CCM+ is used by many Hitachi departments.

Hitachi has been developing nuclear power technology since 1957, and it established HGNE in partnership with General Electric (GE) in 2007. HGNE has the world's top share in ABWR construction. It has received orders for new nuclear power plants that will operate in two locations in the United Kingdom starting in 2020, Wylfa Newydd on the Isle of Anglesey and Oldbury-on-Severn in South Gloucestershire.

Noriyuki Takamura's group in HGNE's Nuclear Power Plant Department has been working on designing and developing piping systems, while Dr. Shiro Takahashi of Hitachi's Nuclear Power Systems Research Department has been researching supersonic-steam-jet phenomena with CRIEPI, which has been investigating maintenance optimization by quantifying external impact when pipes rupture.

For this white paper we spoke with Takahashi about the use of CFD for ABWRs, which incorporates Japan's latest nuclear power plant technology.

Advanced boiling water reactors

The boiling water reactor (BWR) shown in figure 1 carries out nuclear fission by absorbing neutrons using uranium in the nuclear reactor. The resulting heat energy causes light water (ordinary water) to boil, generating high-temperature, high-pressure steam. This steam's thermal energy causes turbines to rotate, producing electricity via generators.

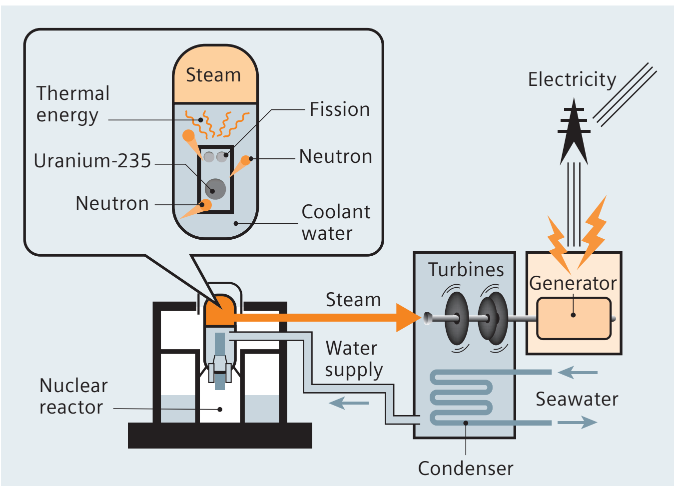


Figure 1.

The ABWR is an advanced version of the BWR and provides improved safety and reliability, reduces radioactive waste and costs, and improves operability and ease of use. The main improvements include:

1. The internal pumps for nuclear reactor coolant recirculation have been housed inside the pressure vessel, piping has been simplified and safety has been improved, all while reducing the amount of radiation to which maintenance personnel are exposed
2. The control rod drive mechanism is equipped with an electric motor drive system in addition to a hydraulic drive system, improving safety by diversifying the drive mechanism
3. The nuclear reactor containment vessel has been integrated into the reactor building, improving earthquake resistance by giving the reactor building a low center of gravity

The Nuclear Power Systems Research Department in Hitachi's Rinkai plant conducts research into element technologies related to nuclear power generation, including secure systems, multi-phase flow, heat transfer and equipment reliability. Takahashi is engaged in R&D on the reliability of equipment and piping inside nuclear power plant reactors.

Using CFD in nuclear power station piping designs

The safety and reliability of piping is a key consideration in designing nuclear power stations. The main steam pipe shown in figure 2 sends high-temperature, high-pressure steam generated in the nuclear reactor to the steam turbines, so designers need to bear in mind various phenomena. This is why CFD and structural simulations are used to design the main steam system piping, and determine optimum pipe systems.

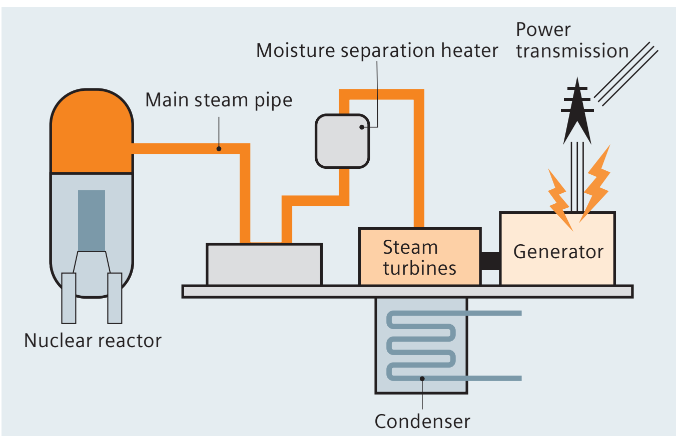


Figure 2.

Ruptured pipes are events that are hypothesized when designing piping. If pipes rupture in the high-temperature, high-pressure steam system or water supply system, steam jets would be produced at the fracture surface, conceivably erupting into the atmosphere faster than the speed of sound. High-temperature, supersonic steam jets that might occur could affect safety equipment and piping in that area, and could cause an industrial accident.

Thus, Simcenter STAR-CCM+ was used to analyze and assess the shapes and fluid force of steam jets erupting from the ruptured portions in the case of main steampipe ruptures.

It is important to assess steam jet shapes (their range of impact) and fluid force (strength) when designing preventive measures for pipe ruptures. To prevent domestic pipe ruptures up until now, piping layout designs were undertaken and pipe whip restraints installed according to assessments based on specifications and standards from the American National Standards Institute (ANSI) and the Japan Society of Mechanical Engineers. This research had the goal of performing detailed evaluations based on the physical phenomena of steam-jet patterns (their range of impact) and fluid force derived from CFD.

- *Pattern assessment:* Steam-jet spread angles confirmed and their range of impact assessed
- *Fluid force evaluation:* Fluid-force actions on structures evaluated by modeling collided structures

As figure 3 shows, a steam jet's shape at the time of a hypothetical pipe rupture swells rapidly from area 1 to 2, spreading while steadily mixing with surrounding fluids in area 3. Simulating changes in the spread angle via CFD was the point of the pattern evaluation. It was also confirmed in the pattern assessment that changes in the shape of the steam jet (shock wave) could be simulated when having it changed from low to high pressure. Further, column-shaped structures were installed as targets in the experiment, and analysis models for the evaluation of fluid force and the loads that affected column-shaped structures were assessed.

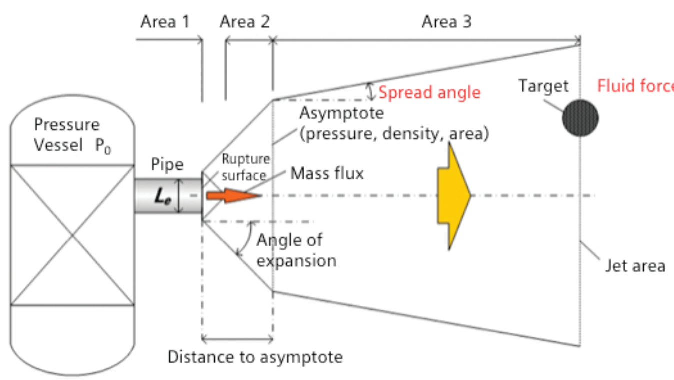


Figure 3.

Choosing Simcenter STAR-CCM+

Takahashi had used Siemens Digital Industries Software's Simcenter STAR-CD® software and had previously praised the firm's technical support capabilities and physical models. He has also praised the extreme robustness of the automated mesh capability and solver in Simcenter STAR-CCM+. Additionally, he has confirmed by comparing experimental results that physical phenomena can be precisely reproduced for analysis objects. Extremely robust, stable solvers were particularly necessary for this analysis because jets that exceeded the speed of sound would be generated and pressure would change greatly before and after the shock wave. Moreover, the ease of meshing in Simcenter STAR-CCM+ was also a reason for the choice because a plant's geometry is extremely complex.

Evaluating jets erupting from pipes

Overview of test equipment

In this section we will provide information about the test equipment used to verify the analyses. CRIEPI's steam testing facilities were used to conduct these experiments.

Steam jet shapes were evaluated by measuring flow-velocity profiles using particle image velocimetry (PIV). A column-shaped structure was set up downstream from the steam jet, and fluid force was assessed from the amount of strain produced by the load from the steam jet (a strain gauge was installed on the lower end of the column-shaped structure). Figure 4 shows a diagram of the test device and figure 5 shows the test device and a photo taken during the implementation of PIV.

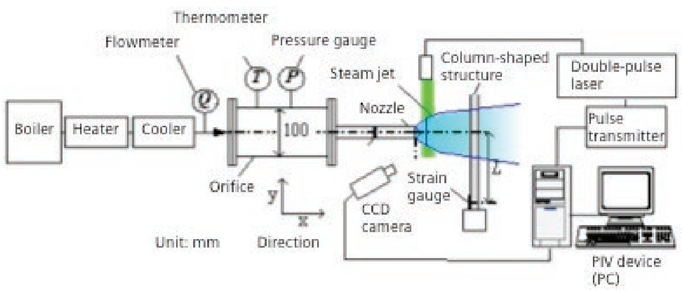


Figure 4.

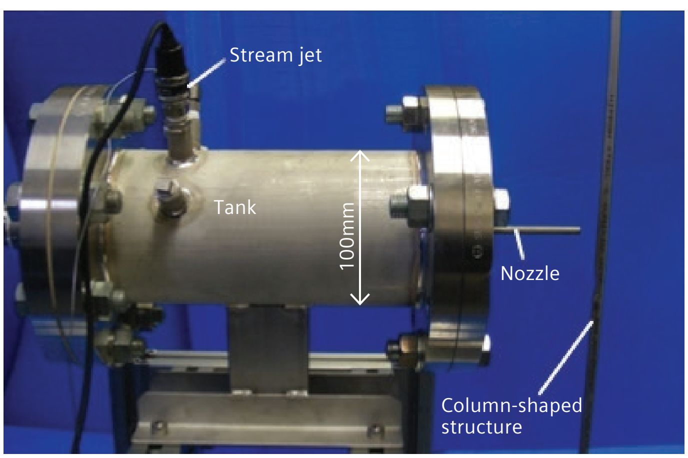


Figure 5a.

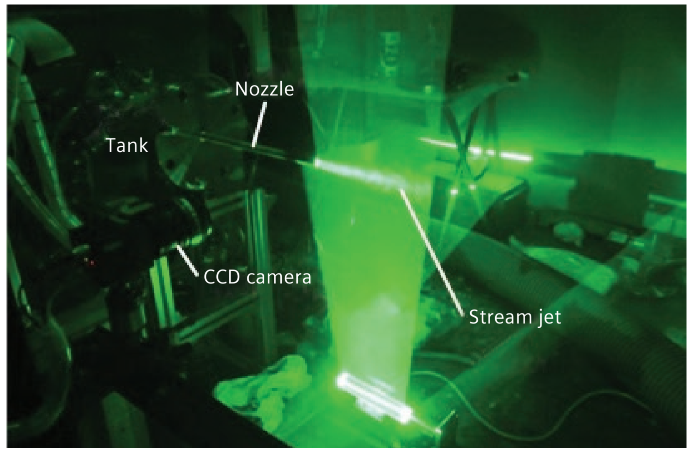


Figure 5b.

Evaluating the shape of the steam jet's expansion

Figure 6 shows the analysis mesh (with 1.7 million cells) used to evaluate the shape. Using the polyhedral mesh in Simcenter STAR-CCM+, prism layer meshes were used for the nozzle's internal walls.

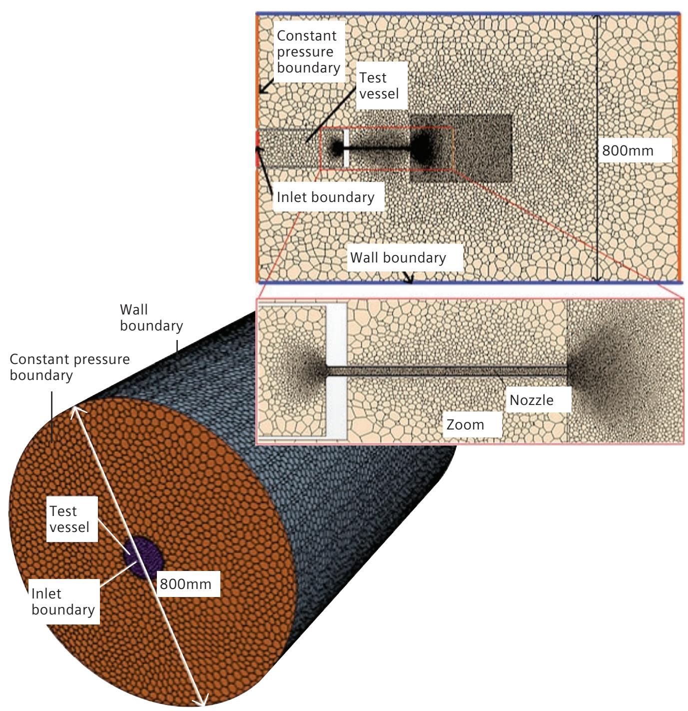
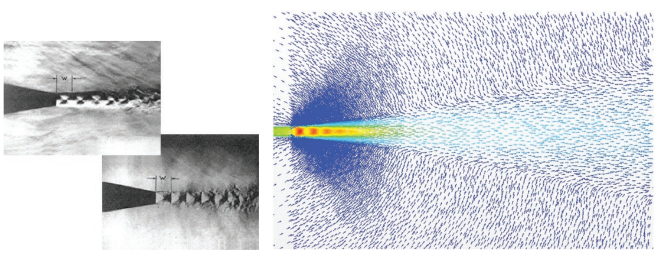


Figure 6.

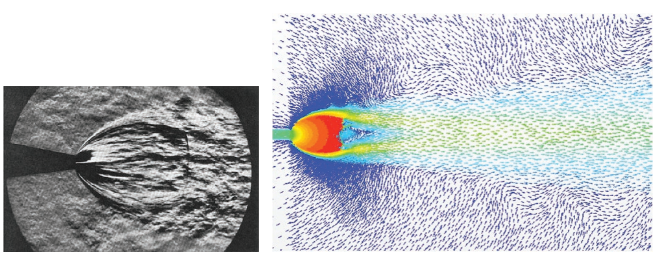
A SST k–ω model was used for turbulence modeling. This helps solve adverse pressure gradients and clearly reproduce shock waves. Physical properties were examined in comparison with other models, and the International Association for the Properties of Water and Steam Industrial Formulation 1997 (IAPWS IF-97) was used, as it was able to reproduce experimental results. The inlet boundary's stagnation pressure was changed from 0.4 to seven megapascal (MPa) as an analysis condition. Additionally, the experiment device's nozzle edges were measured and rigorously modeled when creating the analysis mesh so the shape of the fracture surface would have an impact on the jet's spread angle.

The analysis results are shown below. The following validations were conducted to evaluate steam jet shapes.

1. Changes in shock wave shapes under changing pressure – Shock waves feature a diamond wave pattern when pressure is low and a barrel pattern when pressure is high. As such, the first step in verifying the analyses was to verify whether the analyses could reproduce these patterns. Figure 7 shows the analyses' results. Density was treated as an ideal gas for the purposes of CFD because the fluid used was air. The experimental images were excerpted from a paper entitled, "Experimental and Theoretical Studies of Axisymmetric Free Jets."[1] Love, Eugene S., Grigsby, Carl E., Lee, Louise P., Woodling, Mildred J., NASA Technical Report number NASA-TR-R-6, 1959. As the CFD results show, there is a diamond wave pattern when pressure is low and a barrel pattern when pressure is high, confirming that CFD could be used to reproduce this.



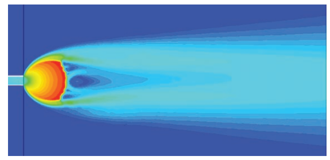
a. Low pressure (0.4MPa): Diamond wave pattern



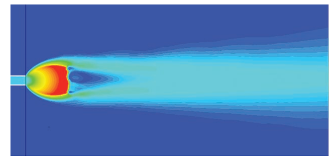
b. High pressure (7MPa): Barrel pattern

Figure 7.

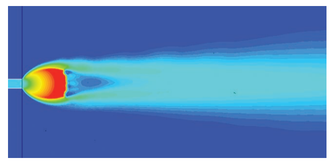
2. Real gas model impact validation – The impact of the physical properties modeling on the steam jet shape was validated. Figure 8 shows the variations in Mach number distribution when the physical properties model is changed. The stagnation pressure was seven MPa. Differences in the physical properties model yielded variations in the shape of the steam jet. It was decided to use IAPWS IF-97 after comparing the experiment results



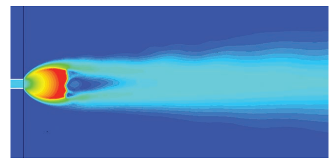
IAPWS IF-97



Redlich-Kwong model



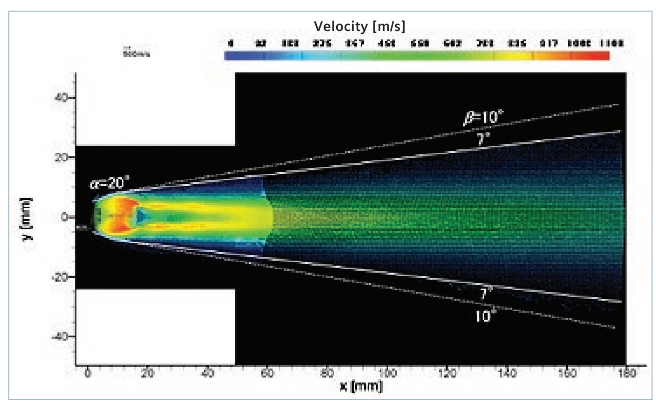
Modified Soave-Redlich-Kwong model



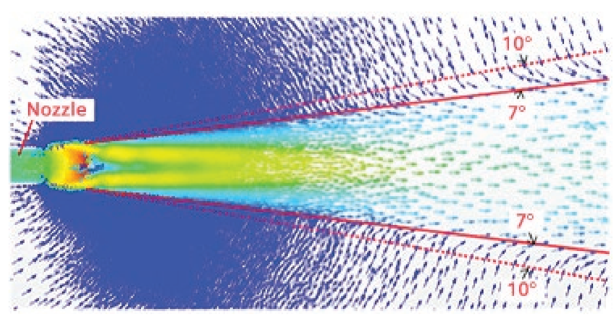
van der Waals model

Figure 8.

3. Comparisons of steam jet patterns derived from CFD and PIV – They compared the steam jet patterns derived from CFD via PIV test results. As figure 9 shows, the steam jet patterns derived from CFD reproduce the experimental results extremely well.



PIV tests: Tank pressure P=0.58 MPa



CFD Stagnation pressure P=0.58 MPa

Figure 9.

4. Comparisons of flow velocity profiles derived from CFD and PIV – They compared flow velocity profiles derived from CFD via PIV test results at the L/D = 10 and 20 positions. L refers to the distance (meters) in the downstream direction, while D refers to the nozzle's inner diameter (meters). As figure 10 shows, the flow velocity profiles derived from CFD conform with the experiment results. Differences arose in the vicinity of the 0-meter position on the graph's vertex, but these differences are believed to be due to the degradation of the seeding particle (water droplet) tracking in PIV measurement.

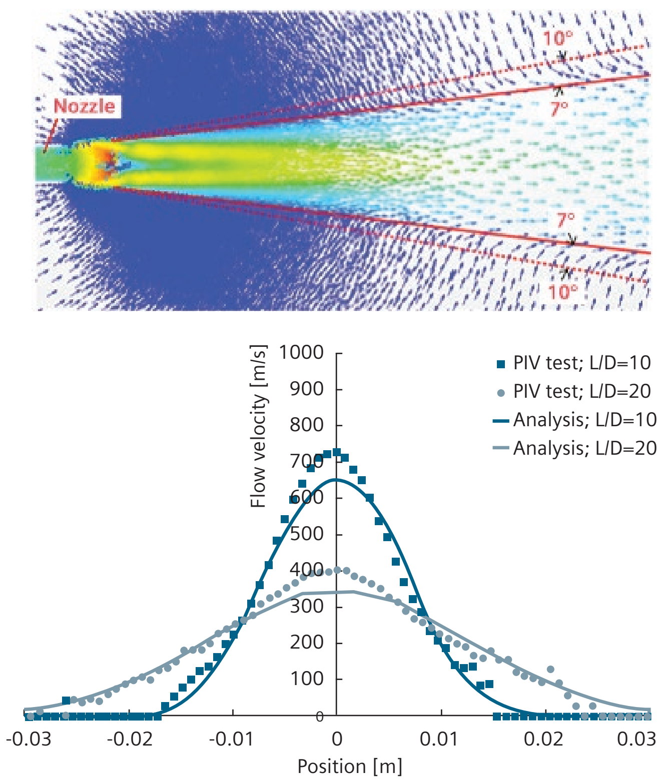


Figure 10.

As figure 11 shows, the jet's width was plotted at the position where flow velocity was about 0 meters per second (m/s) as an assessment of jet shape (impact range). Defining that slope as the spread angle, the spread angle derived from PIV and CFD was seven degrees, and the spread angle of the CFD nearly coincided with the PIV result.

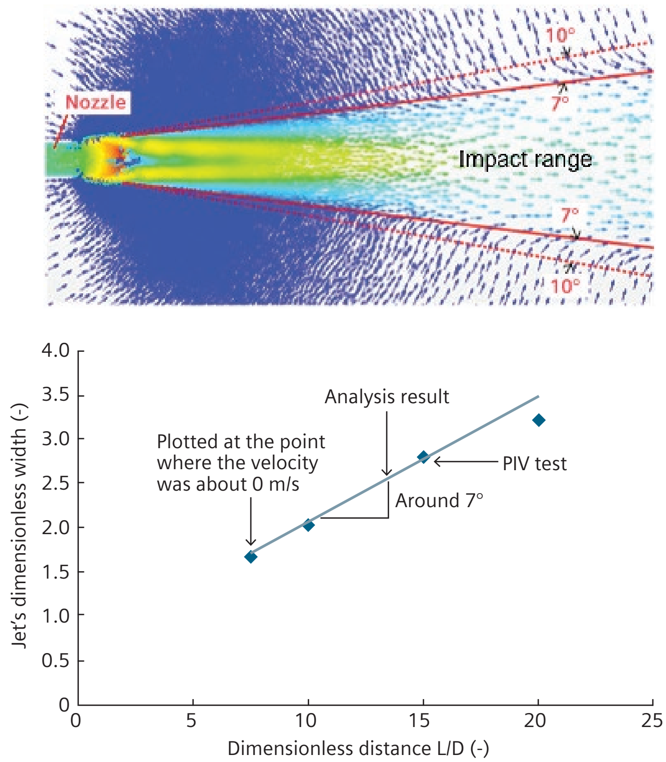


Figure 11.

Fluid force evaluation

Figure 12 shows the computational mesh for the fluid force evaluation. The position in which the column-shaped structure was installed was changed for the fluid force evaluation, and fluid force was compared with experiments and CFD. Figure 13 shows the fluid force vectors derived from CFD. Figure 14 shows the results of the comparison of fluid force in the experiments and CFD. As figure 14 shows, the tests and CFD coincided with a disparity that was under 20 percent. Further, the tendency for fluid force to change was also similar. The disparity between the experiments and CFD was slightly larger in the area near the nozzle, but this was due to the possibility that the column-shaped structure vibrated during the experiments, causing the fluid force to deteriorate. As a result, the tests were thought to assess fluid force lower than the CFD results

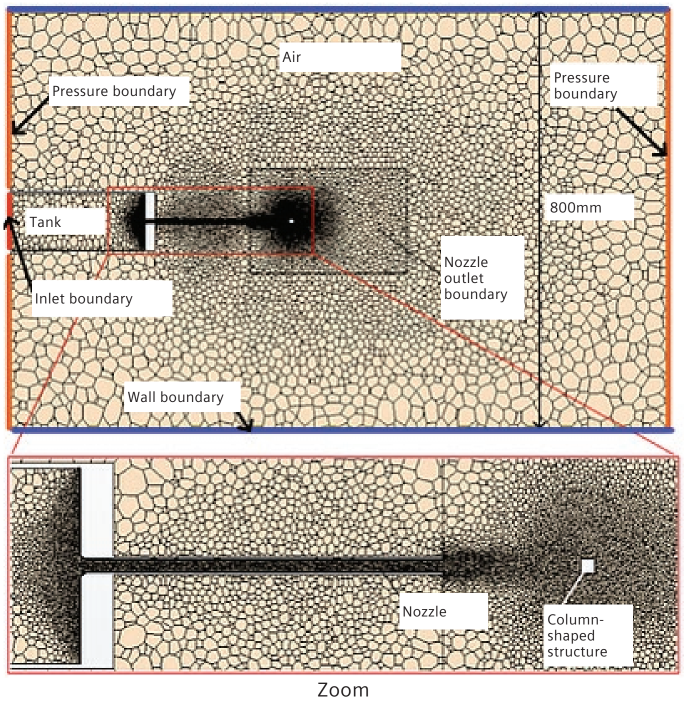


Figure 12.

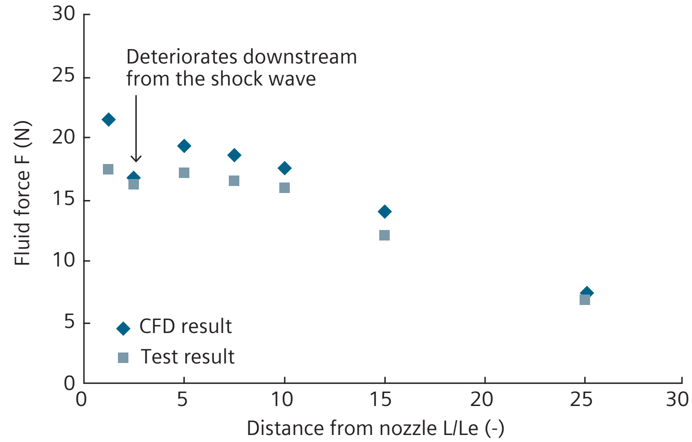
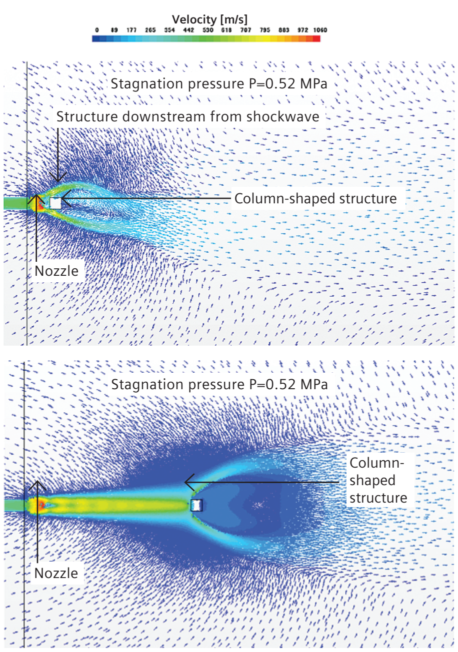


Figure 14.



Column-shaped structure installation position L/Le=2.5

Column-shaped structure installation position L/Le=15

"L" is the distance (in meters), while "Le" is the nozzle diameter (in meters)

Figure 13.

Evaluating the steam jet fluid force

By validating CFD using Simcenter STAR-CCM+ for the supersonic steam jets that occur at the time of a hypothetical pipe rupture by comparing the results derived from CFD of steam jet patterns and fluid force with those from PIV tests, the following conclusions were obtained.

Evaluation of steam jet patterns

The spread angle and flow velocity profile derived via CFD nearly coincided with the PIV test results, confirming that Simcenter STAR-CCM+ was suitable for assessing steam jet patterns.

The fluid force derived via CFD conformed with the experimental results with a disparity of under 20 percent, and at the same time the tendency for fluid force to change was also similar, confirming that Simcenter STAR-CCM+ could be used to evaluate steam jet fluid force.

Conclusion

Nuclear power plants are being designed in accordance with safety specifications and standards derived from numerous full-scale experiments. Advances in CFD have been accompanied by not just designs based on specifications and standards, but the possibility of sophisticated equipment and piping designs that take into account physical phenomena.

The CFD validations of steam jets at the time of hypothetical pipe ruptures were able to confirm that Simcenter STAR-CCM+ is sufficiently precise to reproduce these types of complex phenomena. Further, CFD has become an essential tool for identifying the causes when trouble occurs at nuclear power plants and explaining the phenomena. Nuclear power plant designs have a great impact on society, so it is no surprise that even in the design and development phases, power plants are being built based on verification with these types of robust experiments and CFD. We do not view this simply as providing tools for developing products, but as playing a role in social infrastructure and humanity's prosperity by continuing to assist in finding better designs faster.

References

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   Morita, Ryo, Uchiyama, Yuta, Watanabe, shun, Takahashi, Shiro, Xu, Qiang, Takamura, Noriyuki, “Evaluation of Jet Impact Region and Fluid Force Generated From Ruptured Pipes: 1 – Numerical and Experimental Evaluation of Affected Region by Steam Jet,“ International Conference on Nuclear Engineering (ICONE) paper number 24-60341

   Takahashi, Shiro, Xu, Qiang, Takamura, Noriyuki, Morita, Ryo, Uchiyama, Yuta, Watanabe, Shun, “Evaluation of Jet Impact Region and Fluid Force Generated From Ruptured Pipes: 2 – Evaluation of Fluid Force Using Computational Fluid Dynamics Analysis,“ ICONE paper number 24-60341

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