Numerical Investigation of Sodium Spray Combustion Test with SPHINCS code

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Abstract. As a collaboration on the field of advanced reactor modeling and simulation in Civil Nuclear Energy Research and Development Working Group (CNWG) between Japan Atomic Energy Agency (JAEA) and Sandia National Laboratories (SNL), information exchange of sodium combustion modeling and experimental data has been carried out. In the collaborative work, a benchmark analysis of Surtsey spray combustion experiments done by SNL has been conducted using SPHINCS code at JAEA and CONTAIN-LMR code at SNL. In this paper, the numerical result of SPHINCS code and the comparison between SPHINCS and CONTAIN-LMR codes are discussed. Furthermore, sensitivity analyses have also been carried out to investigate the influential factor on the experiments.

Key Words: Sodium combustion, Numerical simulation, CONTAIN-LMR, SPHINCS

1. Introduction

The chemical reactivity of sodium with oxygen and water will be a key issue for plant safety of sodium-cooled fast reactor, although it may have little influence on core damage accident directly. When sodium leaks from a cooling system into an atmospheric environment, it will fall as a spray, because its pressure is higher than atmospheric pressure, and then each sodium droplet will burn during its fall to the floor. This sodium reaction geometry is designated as ‘spray combustion’. When unburnt sodium piles up on the floor, ‘pool combustion’ occurs.

In 1995, sodium leakage and a subsequent fire took place in the secondary heat transport system at the Monju prototype fast breeder reactor [1]. After the incident, Japan Atomic Energy Agency (JAEA) has developed new numerical tools that employ mechanistic approaches rather than parametric approaches so as to evaluate complex phenomena related to sodium combustion [2]. SPHINCS is a fast-running zone model sodium combustion code extensively used for safety evaluation [1], [3].

Sodium combustion and subsequent damage of safety functions and the rector building will also take place as a result of a core degradation accident. CONTAIN-LMR is a best-estimate, integrated analysis code for predicting the physical, chemical and radiological conditions in a liquid metal fast reactor containment building. The CONTAIN-LMR code was developed by Sandia National Laboratories (SNL) [4] and is based on the CONTAIN code that was intended primarily for the analysis of light water reactors (LWRs) [5]. In CONTAIN-LMR, the distinctive models for sodium-cooled fast reactors, such as multiple condensable materials, sodium properties, heat transfer from core-debris beds and to sodium pools and sodium-concrete interactions, are implemented as well as sodium spray and pool combustions.

Recently, SNL and JAEA have exchanged information of sodium combustion modeling and related experimental data as a collaboration on the field of advanced reactor modeling and simulation within the Civil Nuclear Energy Research and Development Working Group (CNWG), established by the U.S. – Japan Bilateral Commission on Civil Nuclear Cooperation in 2012.

In the collaborative work, a benchmark analysis of Surtsey spray combustion experiments carried out by SNL has been conducted using SPHINCS at JAEA and CONTAIN-LMR at SNL. In this paper, the numerical result of SPHINCS and the comparison between CONTAIN-LMR and SPHINCS codes has been discussed. Furthermore, sensitivity analyses have been carried out to investigate influential factors on the experiment

2. Surtsey Spray Combustion Experiment [6]

The Surtsey vessel is an American Society of Mechanical Engineers (ASME)-approved steel pressure vessel (FIG.1). It has a cylindrical shape with removable, dished heads attached to both ends, and is 3.6 m in diameter by 10.3 m in height. The Surtsey vessel has a maximum allowable working pressure of 1 MPa at 533 K, but has a burst diaphragm installed to limit the pressure in the vessel to less than 0.9 MPa.

FIG. 1. Surtsey vessel.

The vessel walls and heads are approx. 0.01m thick mild steel and covered with at least 0.1m of fiberglass surrounded by stucco for insulation. A false floor is installed between the lower head and the cylindrical wall section reduces the freeboard volume of the Surtsey vessel to 99 m^3.

TABLE I summarizes the spray test condition conducted inside the vessel (T3 and T4). Since the peak pressure in the vessel could not be evaluated directly in T4 experiment (due to an instrumentation port failure mentioned in TABLE I, this benchmark analysis focuses on the T3 experiment firstly.

TABLE I: SPRAY TEST CONDITION

Test #	T3	T4
Location	In-Vessel	In Vessel
Height of spray (m)	5.3	5.3
Nozzle type (Orifice diameter (mm))	Solid cone (12.3)	Solid cone (12.3)
Amount of sodium (kg)	20	20
Flow rate (kg/s)	1.0	1.0
Mean particle size diameter (mm)	3 – 5	3 – 5
Initial temperature of sodium (°C)	200	500
Melt generator pressure at system dump time (MPa)	2.12	2.12
Measured peak air temperature (°C)	480	1200
Measured peak vessel over-pressure (MPa)	0.006	0.2*
Measured peak narrow view heat flux (kW/m^2)	<1	89
Notes		*Instrumentation port failure

3. Benchmark Analysis of Surtsey T3

3.1.Computational condition

Since a lumped mass model is applied both in CONTAIN-LMR and SPHINCS, the same input data of geometry is set. The computational conditions are shown in TABLE II.

TABLE II: COMPUTATIONAL CONDITION

Terms	CONTAIN-LMR	SPHINCS
Vessel free volume	99m^3	←
Vessel thickness	0.01m(1.0cm)	←
Vessel wall emissivity	0.9 [-]	←
Spray height	5.3m	←
Sodium outlet nozzle velocity	*Terminal Velocity*	0m/s
Duration of leakage	20s	←
Initial Sodium temperature	200ºC	←
Mean droplet diameter (volumetric mean)	2.45mm	←
Sodium pool fire	*Activated*	← *(Ring pool fire)*
Initial gas temperature	288.15K	←
Initial gas pressure	101.3kPa A	←
Oxygen concentration (molar fraction)	0.21 [-]	←

In CONTAIN-LMR code, the velocity of the initial droplet is equal to the terminal velocity. On the other hand, the initial velocity can be set and the governing equation of motion is taken into consideration in case of SPHINCS code. Due to lack of information for the terminal velocity of the droplets calculated in CONTAIN-LMR code, the initial velocity is set to 0m/s in SPHINCS code, as shown in TABLE II. It is also mentioned that the ring pool model, in which the one-dimensional cylindrical nodal segmentation is applied to the sodium pool, is applied in SPHINCS code [2]. On the other hand, a lumped mass treatment is also applied in the sodium pool in case of CONTAIN-LMR code. The influence of the pool combustion on the benchmark analysis will be discussed later.

3.2.Results and Discussion

The result of benchmark analysis is shown in FIG. 2, including vertical temperature profile recorded at thermocouple heights within the vessel. In the short period of the experiment (around 100s from the leakage), the pressure and the temperature in the SPHINCS code are overestimated comparing with those of the experiment and the CONTAIN-LMR code. It is concluded that the spray combustion rate in the SPHINCS code larger than that in the CONTAIN-LMR.

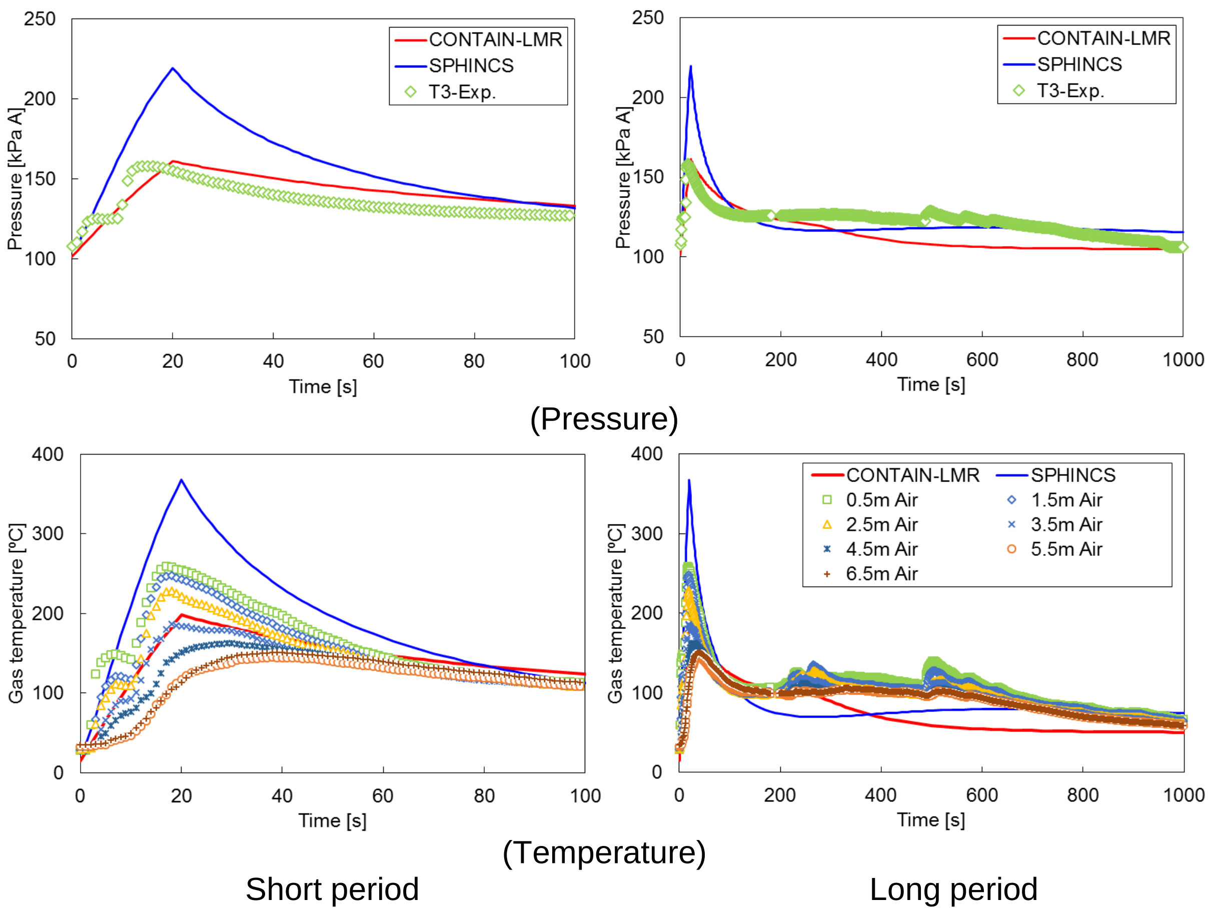


FIG. 2. Comparison between CONTAIN-LMR and SPHINCS.

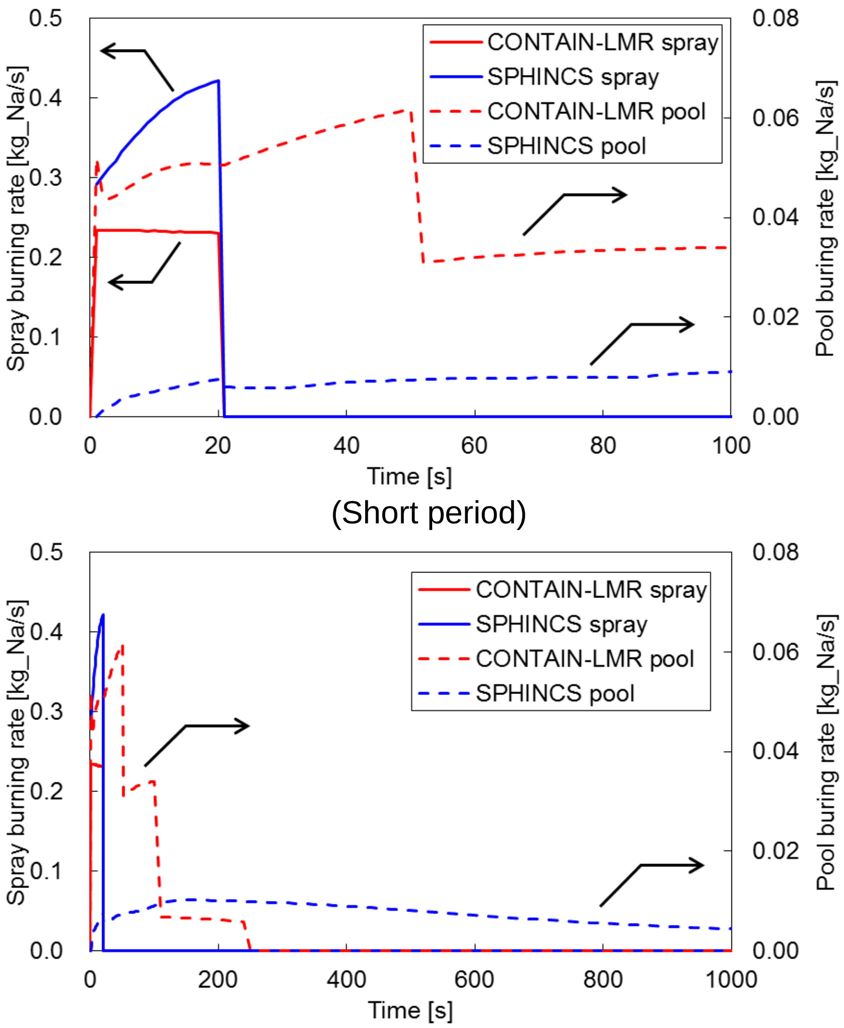
As shown in TABLE I, the initial droplet velocity is set to 0m/s in SPHINCS code. On the other hand, the initial velocity is instantaneously set to its terminal velocity (for instance, terminal velocity of the present mean diameter is approx. 8m/s) in CONTAIN-LMR code.

Since the spray height is 5.3m, the initial velocity will strongly affect the plunge time of the droplet onto the floor resulting in the overestimation of the spray combustion rate in SPHINCS code. The influence of the initial velocity will be discussed in the sensitivity analysis.

It is also noted that the pressure and the temperature increases are suppressed from 3-10s in the experiment. In the video observation, a flashing was observed around 10s. Thus, the spray combustion in the experiment might also be suppressed at that duration. It is also mentioned that the modification of the droplet motion in CONTAIN-LMR code is ongoing. The detailed comparison coming from the initial velocity will be discussed in the near future.

In the later stage, the pressure in the CONTAIN-LMR seems to be underestimated as seen in the right side of FIG. 2. When a lumped mass model is applied in the pool combustion with a comparative small leakage rate, the sodium pool covers all of the floor area instantaneously and thus the heat transfer from the pool to the floor tends to be overestimated resulting in a lower pool combustion rate. The influence of the pool combustion on the later stage of the experiment is also discussed in the sensitivity analysis.

FIGURE 3 shows the comparison between the spray and the pool combustions both in CONTAIN-LMR and SPHINCS codes. With regard to the spray combustion rate (solid lines in FIG.3), a constant burning rate is evaluated in CONTAIN-LMR code. On the other hand, the spray combustion rate increase gradually during the leakage in SPHINCS code.



(Long period)

FIG. 3. Sodium burning rate in SPHINCS

As seen in the pressure transient in FIG. 2, it can be said that the pressure difference between the codes is almost proportional to the difference of the spray combustion rate. In the spray combustion model of SPHINCS code, the burning rate increases as the droplet temperature rises. Since the air temperature increases as in FIG.2, the spray combustion rate also increase gradually in SPHINCS code. The details of the comparison of the spray combustion model will be considered in the future collaboration. The total amount of sodium burnt in the spray is approximately 4.7kg in CONTAIN-LMR and 7.4kg in SPHINCS.

As concerns the pool combustion rate, considerable higher combustion rate is evaluated in the CONTAIN-LMR than that in the SPHINCS in the short period. This is attributed to the fact that the pool area spreads immediately in CONTAIN-LMR code. However, the combustion rate in CONTAIN-LMR decreases suddenly and the pool combustion runs out at 250s. The total amount of sodium burnt in the pool combustion is approximately 5.2kg. In the CONTAIN-LMR, the total burnt sodium is approximately half of the total amount (9.8kg). In the computation, the unburnt sodium temperature decreases due to the heat transfer to the floor resulting in a lower limitation of the pool combustion. In case of SPHINCS code, almost constant burning rate is calculated during the computation (1000s) resulting in the higher gas temperature shown in FIG. 2. In the SPHINCS, the total amount in the pool combustion is approximately 7.5kg which is almost one-and-a-half times as large as that in the CONATIN-LMR result.

3.3.Sensitivity Analyses using SPHINCS

In order to investigate the influences discussed with Sec. 3.2, the sensitivity analyses have been carried out using SPHINCS code. In addition to the influences of the initial droplet velocity and the pool combustion, the influence of the mean droplet diameter is also investigated. The sensitivity parameters are summarized in TABLE III. It is noted that 9.34m/s of the initial velocity is calculated from the experimental condition (leakage rate and the cross-sectional area of nozzle).

TABLE III: SENSITIVITY PARAMETERS

Terms	Default	Modified
Mean droplet diameter (volumetric mean)	2.45mm	3.00mm
Sodium outlet nozzle velocity	0.0m/s	9.34m/s
Sodium pool fire	Activated	Deactivated

The results of the sensitivity analyses are shown in FIGs 4-6. With regard to the influence of the mean droplet diameter, almost an inversely proportional effect is investigated in terms of the maximum pressure as in FIG. 4. Since the Surtsey spray experiment is carried out in the closed vessel, it seems that the influence of the mean diameter weakens.

As a result, total amount of burnt sodium is approximately 5.1kg in the spray combustion and 9.0kg in the pool combustion. However, the pressure and temperature tendency at the later stage is less affected due to the increase of the total amount in the pool combustion (7kg -> 9kg).

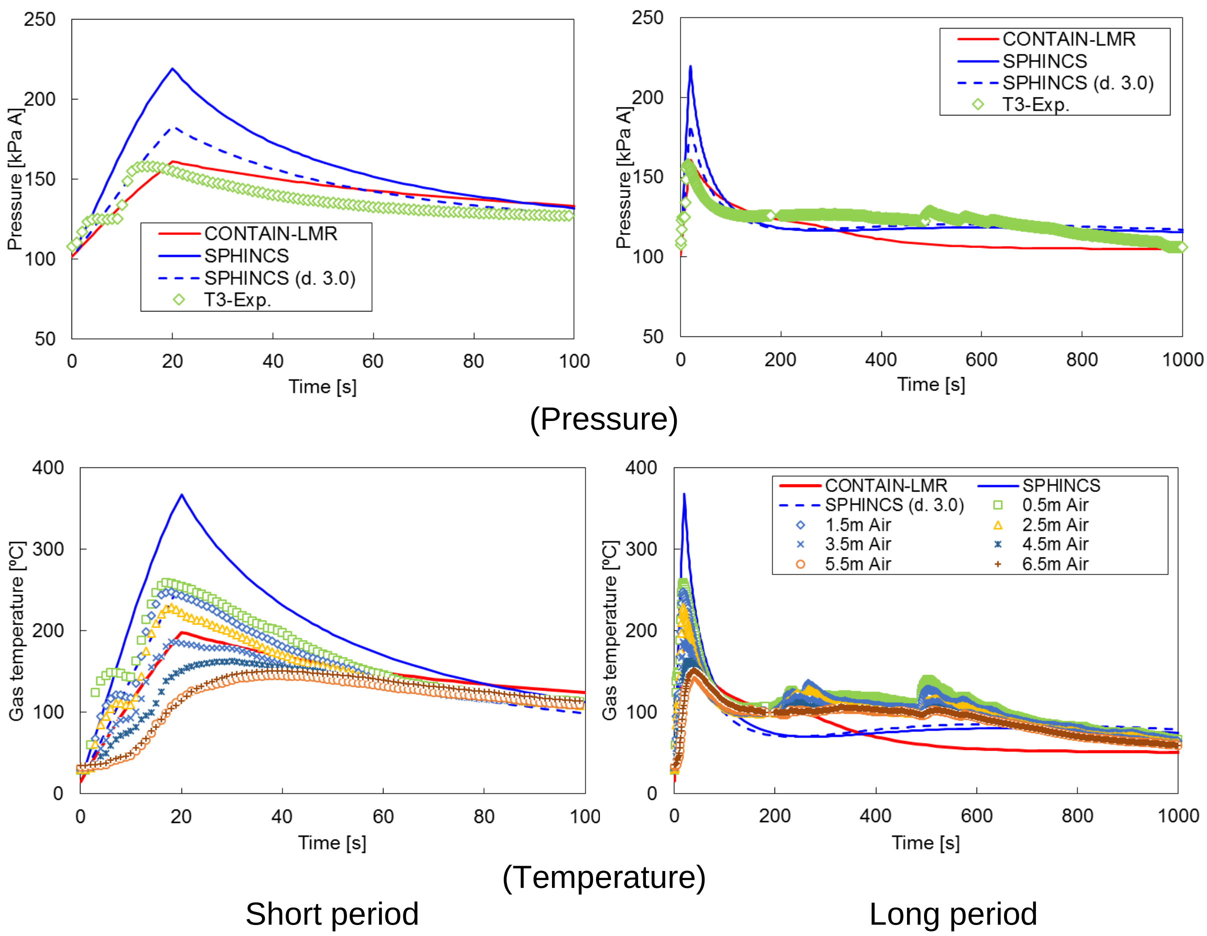


FIG. 4. Influence of droplet mean diameter (SPHINCS)

The influence of the initial droplet velocity is summarized in FIG. 5. Comparing with the influence of the mean diameter, almost the same tendency is observed. This is attributed to the fact that the plunge time of the droplet shortens due to the initial velocity.

When no pool combustion is assumed, it is apparent that the there is almost no effect at the early stage of the experiment as in FIG. 6. On the other hand, the pressure and temperature decrease after 150s from the leakage comparing with the default case. In the computation, almost the same pressure as the ambient pressure is achieved after 400s and the time history of the pressure with no pool combustion agree with that of the CONTAIN-LMR. With regard to the gas temperature, it reaches lower than that in the CONTAIN-LMR as seen in FIG. 6.

In case of a considerable sodium leakage, the difference between the lumped mass model in CONTAIN and the ring model in SPHINCS has less influence. However, in case of a comparative small leakage observed in T3 experiment, one needs a detail discussion of each model.

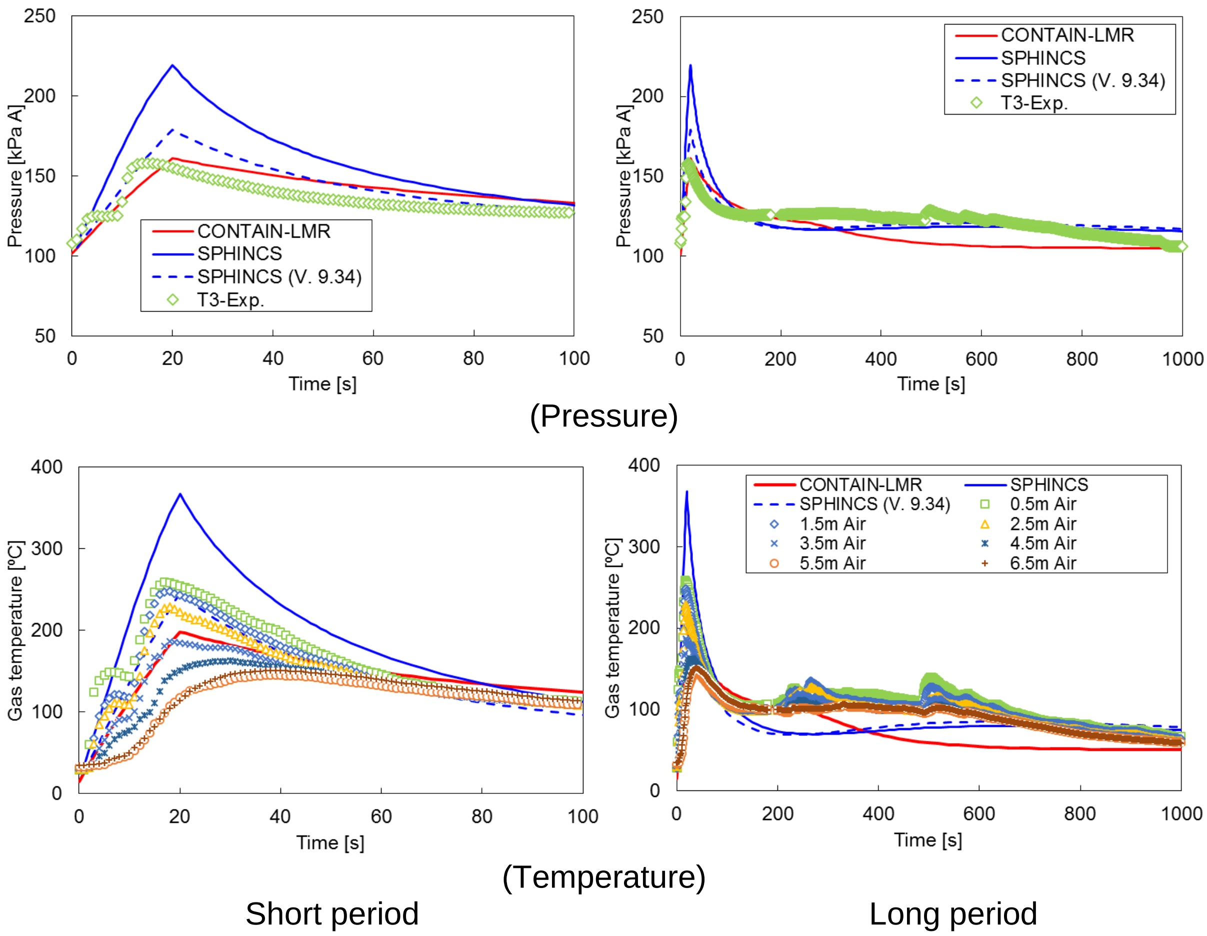


FIG. 5. Influence of droplet initial velocity (SPHINCS)

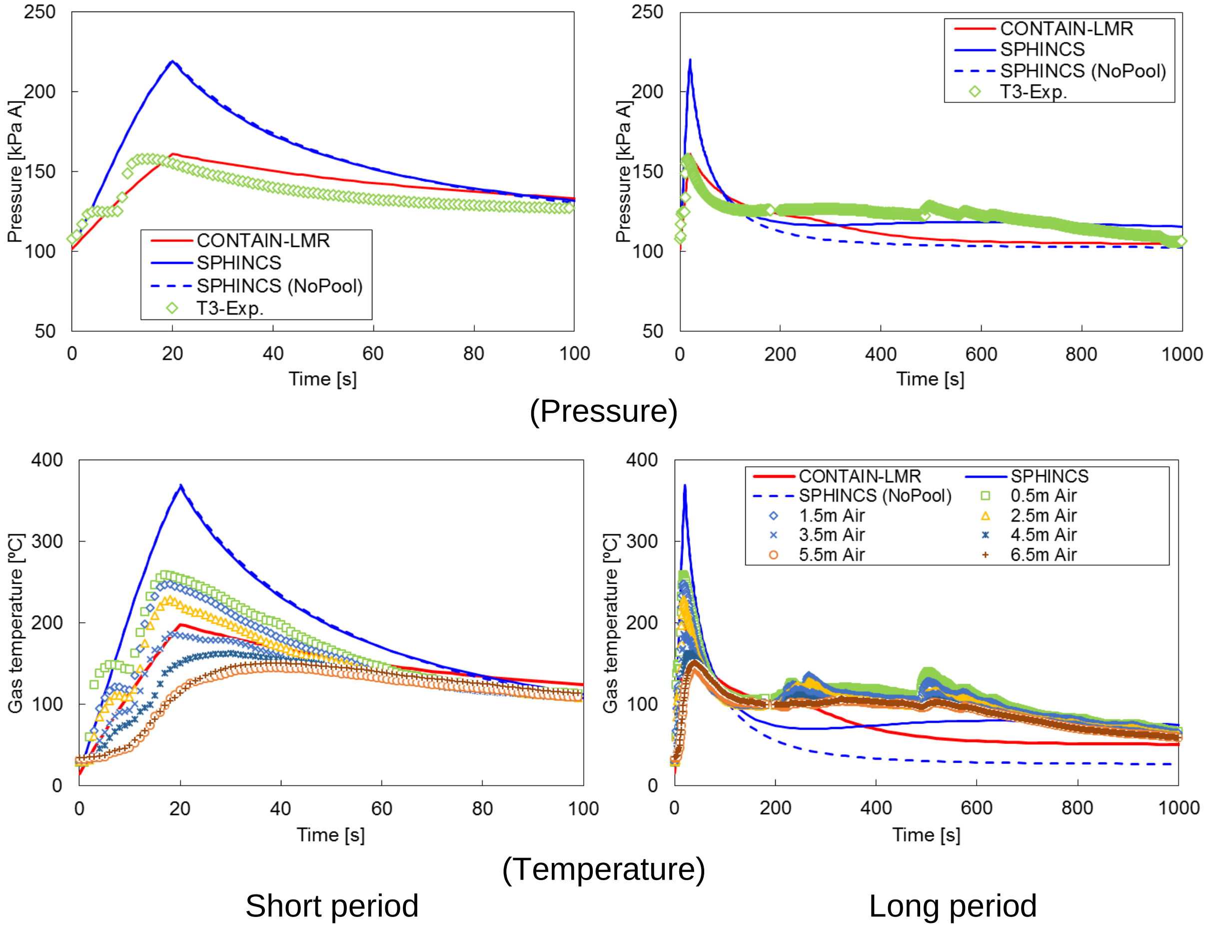


FIG. 6. Influence of pool combustion (SPHINCS)

4. Conclusion

The benchmark analysis of the Surtsey spray combustion experiment T3 has been carried out with the CONTAIN-LMR code by SNL and SPHINCS code by JAEA as a collaborative work of the CNWG. As a result, it is demonstrated that some disagreements are investigated in terms of the initial droplet velocity in the spray combustion and the burning rate of the pool combustion. In the collaborative work, information exchange of the combustion models and the modification of the models have also been discussed. More detail comparison of the codes will be carried out in the near future as well as other benchmark analyses of the sodium combustion experiments carried out both by SNL and JAEA.

The sensitivity analyses of the experiment have also been conducted using SPHINCS code. It is concluded that the initial droplet velocity strongly impacts the maximum pressure behavior because of the change of the plunge time of the droplet. It is also demonstrated that the pool combustion will not be negligible when one takes into account the pressure and temperature behavior at the later stage (longer than approx. 150s from the leakage) of the experiment.

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