Effect of top and bottom blowing conditions on spitting in converter

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Abstract
The effect of top blowing and bottom blowing conditions on spitting behavior was investigated by water model experiments and numerical calculation. The results of the water model experiment showed that reducing the jet velocity by using a larger nozzle diameter was effective for reducing spitting. The numerical calculation indicated that interference between the top blown gas jet and the bottom blowing plume increases the gas velocity at the rim of the cavity, causing heavier spitting. A new index using the geometrical locations of the neighboring cavity and plume was proposed. The spitting rate decreased under conditions with lower interference by avoiding interaction between the top blown gas jet and the bottom blowing plume. The energy distribution in the blowing process was discussed based on a water model experiment using bath mixing time, bath vibration, and the spitting rate. The energy for spitting was explained convincingly by the difference between the energy input and the energy of bath vibration, cavity formation, and bath mixing. The results implied lower interference of the top and bottom gas resulted in lower energy for spitting generation.

KEYWORDS
bottom blowing, converter, oxygen steelmaking, spitting, top blowing, water model

1 | INTRODUCTION

In oxygen steelmaking by the converter process, oxygen gas is blown from a top lance, and the carbon in the molten iron is removed as CO gas, while other impurities such as phosphorus and silicon are removed to the slag in the converter. These reactions are affected by the behavior of the molten bath, which includes splashing and spitting, liquid flows, bath homogenization, and bath oscillation.

Increasing the top blowing rate and reducing the blowing duration are important for enhancing converter productivity. However, increasing the top blowing rate increases the momentum of the gas jet, which causes spitting,1-13 and eventually results in iron yield loss. Spitting also has other detrimental effects, as it causes skulling of the converter cone and mouth and reduces lance life.

On the other hand, the bottom blowing gas forms a plume, and the plume eye is exposed without cover slag.
Considering these facts, not only the momentum of the top blown gas jet, but also the configuration of the top blown gas jet and the bottom blowing plume plays very important roles in the spitting phenomenon. Quite a few papers have presented the results of numerical simulations of the top blown jet or evaluations of spitting by water model experiments. It is known that reducing the momentum of the top blown gas jet at the surface of the molten steel is effective for suppressing spitting.\(^8\)\(^,\)\(^10\)\(^,\)\(^11\) Several approaches are available for reducing the jet momentum, for example, utilizing incorrect expansion of the Laval nozzle and reducing the jet momentum by expansion loss of the jet,\(^11\) or avoiding overlap of the jets by using a nozzle twisted lance\(^13\) and a lance with a different nozzle diameter and tilting angle.\(^10\)

The momentum of the top blown jet is consumed by various phenomena that occur in a converter, particularly bath stirring, spitting and cavity formation. Previous papers have stated that the energy consumption ratio of spitting increases with increased input energy,\(^14\) and the energy for cavity formation is much larger than the spitting energy in systems with high density liquids.\(^6\)

As for influence by slag existence, Li et al\(^15\) carried out numerical simulation and stated that kinetic energy of top blown jet is consumed about a half to drive the movement of slag. They also reported that cavity profile and interface of slag/metal/gas remain unstable because of surface waves fluctuation, affecting the generation of the metal droplet and their initial size distribution. Li et al\(^16\) also showed numerical simulation results with slag existence. They showed larger lance height results in better energy transfer efficiency.

However, those papers mostly investigated top blowing conditions. Few reports have examined top and bottom combined blowing, and those reports mainly discussed the effect of combined blowing conditions on mixing behavior or mass transfer between the slag and the metal.\(^14\)\(^-\)\(^24\) Fabtritus et al\(^25\) and Luomala et al\(^26\) discussed the effect of top and bottom blowing conditions. They reported that the degree of overlap of the top blown gas jet and the bottom blowing plume changes the direction of spitting\(^25\) and bath oscillation,\(^26\) and eventually spitting increases in comparison with conditions without bottom blowing. Zhou et al\(^27\) focused on kinetic energy transfer into the bath of BOF (Basic Oxygen Furnace) by numerical simulation, showing the bottom configuration affects kinetic energy into bath metal. These paper implies that spitting rate and energy distribution may change by bottom configuration. However, their reports assumed simple or a symmetric converter configuration, but the actual converters of recent years have complex bottom tuyere configurations with asymmetric locations, different circle pitches, and so forth.

In this study, the authors focused on the spitting phenomenon. The spitting rate was evaluated with a water model under various combined blowing conditions. In addition to bath mixing and bath vibration, energy consumption by the spitting phenomenon was also investigated, and the effect of the bottom tuyere configuration on the energy distribution in the blowing process was discussed.

### 2 | EXPERIMENTS

Measures for spitting reduction by modification of the top blowing process have been investigated in a number of previous studies. For example, Higuchi et al\(^10\)\(^,\)\(^12\) reported that avoiding overlap of the top blown jets results in a lower dynamic pressure on the metal surface, and this reduces spitting. However, in operation with a larger top blowing rate, the mass flow rate of the oxygen inevitably increases, and under this condition, the only way to achieve low kinetic energy of the jet is to reduce the gas velocity on the bath surface. There are two options for reducing the jet velocity, lowering the velocity at the nozzle end by enlarging the nozzle diameter, or taking advantage of the attenuation of the jet with a smaller nozzle diameter. The investigations in this study were carried out with a water model. As a first step, (1) the effect of enlarging the nozzle diameter on reduction of the kinetic energy of the top blown gas jet was investigated. Following this, (2) the effect of the bottom blowing conditions on the spitting phenomenon was examined under the same top blowing conditions.

A schematic diagram of the experimental apparatus is shown in Figure 1. An acrylic vessel which is a 1/10 scale model of an actual converter was used as the water model. Since it is known that liquid with similar kinetic viscosity shows similar behavior, water was employed to simulate hot metal. For simplicity, water model experiments were carried out without slag phase. In the bottom, a bottom plate with several tuyeres was attached with a flange. The tuyere diameter was 2 mm, and nitrogen gas was supplied through a nylon tube. The tuyere configuration could be changed in various ways by using different bottom plates. For top blowing, nitrogen gas was supplied through a stainless tube (25A). Stainless lance tips with various nozzle specifications (number of nozzles, nozzle diameter and tilting angle) were attached to this tube.

Table 1 shows the experimental conditions. To avoid the effect of interaction of the neighboring top blown jets, the number of nozzle holes was limited to 4 or 5. The bottom tuyere configuration was changed variously with 4, 6, 8, or 10
FIGURE 1  Schematic view of water model experiment

![Schematic view of water model experiment](image)

TABLE 1  Experimental conditions

| Number of nozzles [-] | Tilting angle [°] | Nozzle diameter [mm] | Top blowing rate [Nm³/min] | Lance height [mm] | Bottom blowing rate [Nm³/min] |
|----------------------|-------------------|----------------------|---------------------------|-------------------|-------------------------------|
| 4, 5                 | 14–21             | 4.9, 6.6, 7.4        | 1.2                       | 180, 250          | 0.025                         |

Tuyeres. Top blowing rate and bottom blowing rate were determined so as to satisfy the condition of the same modified Froude number as in practical operation. When blowing top and bottom gas, the spitting rate, mixing time and bath vibration were measured. The measurement procedures are described in the following.

2.1  Spitting rate

Eight spitting capturers (cup filled with a polymer absorber, φ30 mm x h 10 mm) were set downwards 350 mm above the bath level. The capturers were positioned as shown in Figure 1. After blowing under a constant condition (top blowing rate, lance height, bottom blowing rate, and blowing period), the spitting capturers were collected. The spitting rate $R_{sp}$ was determined by the total weight change due to capture $\Delta W_{ab}$ [g] and the blowing duration $\Delta t$ [min] by using Equation (1).

$$R_{sp} = \frac{\Delta W_{ab}}{\Delta t}$$ (1)

For operability of experiment, spitting capturers’ position was on above trunnion axis, which showed similar tendency as measurement with spitting capturers located on circle. (P.C.D = 330 mm).

2.2  Mixing time

Top gas and bottom gas were blown at a predetermined flow rate. After the gas flow rate stabilized, a 15 ml KCl solution was dropped using a funnel. The conductivity of the water bath was measured every 0.2 s by a conductivity meter and logged using a data logger (Graphtech GL220). The conductivity meter was located opposite to the tracer injection point at a level 30 mm from the bottom. An example of the results of a conductivity measurement is shown in Figure 2. The mixing time was defined as the time at which the conductivity of the water at the probe converged to within 2% of the steady state value.
2.3 Bath vibration

The bath level was measured by laser level displacement meters (Keyence, IL600) placed 500 mm above the bath surface. Peak to peak value of bath level, H, was determined by measuring the bath level every 0.2 s for 490 s. \( H \) was defined as the difference between the maximum bath level and the minimum bath level. Measured \( H \) values by two laser displacement meters showed similar value within 2 mm. Average value of \( H \) measured by two laser displacement meter was employed as \( H \).

To measure the bath level displacement, rice water was added to suppress diffused reflection of the bath surface. In this measurement, however, the displacement meter often detects spitting water droplets, as shown in Figure 3. So, the bath level with outlying value was omitted. For this reason, bath vibration was evaluated by using a combination of the bath vibration amplitude measured by the laser displacement meter and the bath acceleration measured by an accelerometer.

An accelerometer (PCB Piezotronics, 3711B112G) was attached to the trunnion of the water model vessel, and the acceleration in the trunnion axis was measured. Signals from the accelerometer were processed with a FFT analyzer (OROS, OR34) for 490 s in each experiment. Here, 490 s is determined since duration in which oxygen flow rate and lance height remain constant is about 5–10 min in actual converter.

The acceleration signals of the last 80 s were analyzed, and the frequency with the maximum acceleration was logged. Frequency analysis was performed at intervals of 10 s from the first analysis.

The frequency of bath vibration \( f \) was determined from the frequency values of 42 analyzed points. The frequency distribution of bath vibration is shown in Figure 4. Since the average frequency is affected by high frequency measurements, even though these are observed only a few times, the frequency which was most frequently logged by the FFT analyzer was defined as the frequency of bath vibration.

2.4 Simulation

For qualitative observation of the effect of the interaction between the top blown gas jet and the bottom blowing plume, the fluid behavior was evaluated by a numerical simulation.
FIGURE 4  Distribution of frequency of vibration

TABLE 2  Parameters used in the present simulation

| Items                      | Unit | Value   |
|----------------------------|------|---------|
| Density of water (at 20°C) | kg/m³| 998     |
| Dynamic viscosity of water | Pa s | 0.001   |
| Surface tension of water   | N/m  | 0.073   |
| Dynamic viscosity of nitrogen | Pa s | 0.0000176 |

The numerical simulations were carried out using the commercial computational fluid dynamic software STAR-CCM+. The simulations are based on the Reynolds averaged Navier–Stokes equations and the realizable k-ε turbulence model with standard values for the constants. The behavior of the gas–liquid interface was calculated using the Volume of Fluid model. A hexahedral mesh with 1.2 million cells was used. A mass flow rate boundary condition was used to describe the gas supplied from the top lance and the bottom tuyeres, and a pressure condition equal to atmospheric pressure was used at the exit of the vessel. A no-slip boundary condition with a standard wall function was used at the wall of the vessel. For simplicity, the top blown gas jet was blown vertically downward from a single nozzle, and the bottom tuyere was located at the center of the bottom plate. The top and bottom blowing rates were set as the flow rate per single nozzle or single tuyere, and were the same as the conditions in the water model experiment. Nozzle diameter of the top lance, lance height, top blowing rate and bottom blowing rate were 6.1 mm, 250 mm, 300 L/min (ntp), 3 L/min (ntp), respectively. Parameters used in the present simulation are shown in Table 2.

3 | RESULTS

3.1 | Effect of top blowing condition on spitting phenomena

Figure 5 shows the spitting rate with the different nozzle diameters in experiments in which only top blowing was performed. The spitting rate decreased with large nozzle diameters. This is attributed to the effect of the larger diameter in lowering the gas jet velocity at the nozzle end. To confirm the effect of the top blown gas jet velocity, the relationship between the calculated jet velocity at the bath surface and the spitting rate is shown in Figure 6. Although there is a correlation between these two axes, this relationship cannot explain the effect of the number of nozzle holes.

From previous studies, it is known that the momentum of a gas jet has a good correlation with the spitting rate and the interaction between neighboring gas jets may affect spitting phenomena. Assuming that the energy consumed by cavity formation and spitting generation is proportional, the impulse of gas jet input into the bath can be expressed as shown in Equation (2) by the cavity shape.

\[
M_{\text{jet}} = \int \frac{1}{2} \rho g v^2 ds \propto M_{\text{jet}}' = \int (\rho gh) ds
\]  

(2)
Here, \( M_{\text{jet}} \) is impulse of gas jet [N], \( \rho_g \) is density of nitrogen gas jet [kg/m\(^3\)], \( v \) is gas velocity [m/s], \( \rho_l \) is density of water [kg/m\(^3\)], \( g \) is acceleration of gravity [m/s\(^2\)], \( h \) is depth of cavity [m], and \( s \) is section area of cavity at bath surface [m\(^2\)]. The following cavity shape estimation formula for the case when a gas is blown vertically was proposed by Segawa.\(^{30}\)

\[
r_{\text{cavity}} = l \tan(\xi) + \frac{d_e}{2} \quad (3)
\]

\[
L = L_h \exp \left( -\frac{0.78l}{L_h} \right) \quad (4)
\]

\[
L_h = 63.0 \left( \frac{k F_{N2}}{n d_e} \right)^{\frac{1}{3}} \quad (5)
\]

Here, \( r_{\text{cavity}} \) is radius of cavity [m], \( l \) is lance height [m], \( d_e \) is nozzle end diameter [mm], \( \xi \) is gas jet expansion angle [\(^\circ\)], \( L \) is maximum cavity depth [mm], \( k \) is a constant [\(-\)], \( F_{N2} \) is nitrogen gas flow rate [Nm\(^3\)/h], and \( n \) is number of nozzles.

In this study, considering the effect of the tilting angle, Equations (3)–(5) were used to estimate the cavity shape. In addition, assuming that each nozzle has an independent jet, the constant \( k \) was set as 1, which is reported as a value for a single nozzle.\(^{30}\)

\[
r_{\text{cavity}} = \frac{1}{2} \left( \frac{\tan(\theta + \xi) - \tan(\theta - \xi)}{2} + \frac{1}{\cos \theta} \tan \varphi \right) + \frac{d_e}{2} \quad (6)
\]

\[
L = L_h \exp \left( -\frac{0.78l}{L_h} \right) \quad (7)
\]

\[
L_h = 63.0 \left( \frac{k F_{N2}}{n d_e} \right)^{\frac{1}{3}} \cos \theta \quad (8)
\]
Here, $\theta$ is tilting angle of nozzle (°).

Figure 7 shows the relationship between $M_{jet}'$ and the spitting rate. Both the 4-nozzle lance and the 5-nozzle lance conditions show a good correlation. From this fact, the spitting phenomenon caused by the top blown gas jet is mainly due to the kinetic energy of the jet. It can also be said that the interaction between a gas jet and a neighboring gas jet is negligible under the conditions of this study.

### 3.2 Effect of top and bottom combined blowing conditions on spitting phenomena

The results under the top and bottom blowing condition are shown in Figure 8. As is obvious from Figure 8, the spitting rate differed drastically with different bottom tuyere configurations.

In these experiments, the same top nozzle condition was used at the same lance height, and both the top blowing rate and the bottom blowing rate were constant. In other words, the kinetic energy of the top blown gas jet and the bottom blowing plume was the same in these experiments.
Except for the results of the experiments with only top blowing, spitting behavior cannot be explained in terms of the amount of energy. Therefore, in the following discussion, the authors considered the effect of interaction between the top blown jet and the spout formed by the bottom blowing.

4 | DISCUSSION

4.1 | Interaction between cavity formed by top blown gas jet and bottom blowing plume

The results of top and bottom combined blowing showed that the interaction between the top blown gas jet and the bottom blowing plume should be considered. Fabritius et al. reported the possibility of change in the spitting direction with an overlapped cavity formed by the top blown gas jet and bottom blowing plume, which results in a spitting increase.

The CFD (Computational Fluid Dynamics) results for the top blowing condition and the combined blowing condition are shown in Figure 9. Spitting rate was compared with water model experiment with same conditions. Spitting rate without bottom blowing was 0.07 g/min by water model, 0.07 g/min by CFD simulation respectively. For the experiments with bottom blowing, spitting rate was 0.34 g/min by water model experiment, 0.36 g/min by simulation.

Unlike the top blowing condition, the symmetry of the cavity collapsed in combined blowing, and spitting was observed at the asymmetric edge of the cavity. As Sabah et al. mentioned, spitting generation occurs at the rim of the cavity or crushing and tearing of splashings sheets. Also, Li et al. observed similar spitting droplets generation by numerical simulation. In this study, to understand the spitting generation at the rim of the cavity, gas velocity near the cavity of the top blown gas jet was compared in Figure 10. The Position at which velocity was compared, is shown in Figure 9. Pos(1), Pos(2) and Pos(3) are located 39, 60, 82 mm from the center axis of the cavity.

The results imply that gas jet velocity increased by interference between top blown jet and bottom blown plume, causing higher spitting rate.

4.2 | Quantification of top and bottom interference

As mentioned previously, the spitting rate differs drastically depending on the bottom tuyere configuration, and the interference between the top blown gas jet and the bottom blowing plume increases the spitting rate. Therefore, in this study,
Interference was defined in order to quantify the interference between the cavity formed by the top blown gas jet and the bottom blowing plume. A schematic diagram is shown in Figure 11. The conditions of this model are as follows.

1. The bath surface is considered to be a coordinate plane.
2. The origin O of the coordinate is the intersection of the center axis of the converter and the bath surface.
3. The center of the bottom blowing plume \( B_i \) is defined as \( B_i \). The neighboring cavity \( i \) formed by the top blown gas jet is defined as \( C_i \). Here, the neighboring cavity has the minimum distance from the bottom blowing plume. \( N_b \) is the number of bottom tuyeres.
4. Interference of the cavity formed by the top blown gas jet and the bottom blowing plume is considered by using the angular difference \( \phi_i \), the pitch circle radius of the cavity center \( r_t \) and the bottom blowing plume center \( r_{bi} \).
5. \( \phi_i \) is the absolute value of the angle between lines \( OC_i \) and \( OB_i \).

Based on these assumptions and definitions, the interference index \( I_{\text{Interference}} \) is expressed as Equation (9).

\[
I_{\text{Interference}} = \left( \frac{1}{n_b} \sum_{i=1}^{n_b} \frac{r_t}{r_{bi}} \left( 90 - \phi_i \right) \right) \cdot \frac{1}{n_b}
\]  

(9)

When \( I_{\text{Interference}} \) is large, interference is large. Geometries of experiment and calculated interference index values are shown in Tables 3 and 4.

To confirm the validity of \( I_{\text{Interference}} \), the results of the water model experiments were plotted in Figure 12. Even with different nozzle holes and different numbers of bottom tuyeres, there was a good correlation between the spitting rate and \( I_{\text{Interference}} \). This implies that avoiding interference between the top blown gas jet and the bottom blowing plume is effective for reducing spitting. In other words, a bottom tuyere configuration which is suitable for reduction spitting should be designed.
|                      | 1       | 2       | 3       | 4       |
|----------------------|---------|---------|---------|---------|
| **Top blowing lance configuration** | ![config1] | ![config2] | ![config3] | ![config4] |
| Tilting angle [°]    | 20      | 20      | 14      | 14      |
| **Bottom tuyere configuration** | ![config1] | ![config2] | ![config3] | ![config4] |
| Top blowing rate [Nm³/min] | 1.2     | 1.2     | 1.2     | 1.2     |
| Lance height [m]     | 0.25    | 0.25    | 0.25    | 0.25    |
| Mixing time [s]      | 50.3    | 46.8    | 30.8    | 37.9    |
| Amplitude of bath vibration [mm] | 33      | 29      | 26      | 36      |
| Frequency of bath vibration [Hz] | 0.390   | 0.469   | 0.781   | 0.781   |
| Spitting rate [g/min] | 0.318   | 0.370   | 0.099   | 0.095   |

**TABLE 4** Experimental results [five hole nozzles]

|                      | 1       | 2       | 3       | 4       | 5       | 6       | 7       |
|----------------------|---------|---------|---------|---------|---------|---------|---------|
| **Top blowing lance configuration** | ![config1] | ![config2] | ![config3] | ![config4] | ![config5] | ![config6] | ![config7] |
| nozzle holes:5, tilting angle:18° |         |         |         |         |         |         |         |
| **Bottom tuyere configuration** | ![config1] | ![config2] | ![config3] | ![config4] | ![config5] | ![config6] | ![config7] |
| Top blowing rate [Nm³/min] | 1.2     | 1.2     | 1.2     | 1.2     | 1.2     | 1.2     | 1.2     |
| Lance height [m]     | 0.18    | 0.18    | 0.18    | 0.18    | 0.18    | 0.18    | 0.18    |
| Mixing time [s]      | 42.7    | 45.4    | 40.1    | 34.3    | 35.5    | 46.5    | 25.5    |
| Peak to peak value H of bath level [mm] | 53      | 17      | 48      | 38      | 55      | 53      | 24      |
| Frequency of bath vibration [Hz] | 0.680   | 0.625   | 0.625   | 0.630   | 0.469   | 0.680   | 0.586   |
| Spitting rate [g/min] | 0.070   | 0.479   | 0.192   | 0.217   | 0.090   | 0.258   | 0.096   |

### 4.3 Energy distribution analysis

As discussed in Section 3.2, reducing the interference between the cavity formed by the top blown gas jet and the bottom blowing plume results in a reduction in spitting. As in this section, the spitting rate was considered from the viewpoint of energy consumption. Figure 13 is a schematic representation of the energy balance of this experiment. The energy input into the water model system can be classified into the kinetic energy of the top blown gas jet, the kinetic energy of the bottom blown gas and the sensible heat of the blown gas. The energy output, that is, the energy consumed in the system, is classified into spitting energy, bath mixing energy, bath vibration energy, cavity formation energy and the change of sensible heat of the water bath and blown gas. Among these, sensible heat was omitted since the temperature change in water model experiments is relatively small. Bath vibration energy and bath mixing energy can be calculated from the measured results shown in Tables 3, 4 and 5.
4.3.1 Bath vibration energy

Using the measured values of the vibration frequency $f$ and amplitude $H$, the bath vibration energy $E_{\text{vib}}$ (W/t) was calculated. Assuming bath vibration as a sinusoidal wave, energy is derived by multiplying mean value of the wave and area of effective area, and expressed by Equation (10).

$$E_{\text{vib}} = \rho g \cdot \left(\frac{H}{2} \cdot \frac{2}{\pi}\right) f \cdot (\pi DH)/W$$

Here, $\rho$ is density of water [kg/m$^3$], $g$ is acceleration of gravity [m/s$^2$], $H$ is amplitude [m], $f$ is bath vibration frequency [Hz] measured by laser displacement meter, $D$ is diameter of water model [m], and $W$ is bath weight [t].
### TABLE 5 Geometries of top blowing cavity and bottom blowing plume

| Lance design | Lance height | \( r_t \) | \( \theta_1 \) | \( \theta_2 \) | \( \theta_3 \) | \( \theta_4 \) | \( \theta_5 \) |
|--------------|--------------|--------|------|------|------|------|------|
|              | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| Top blowing cavity geometry | | | | | | | |
| Lance height | \( r_t \) | \( \theta_1 \) | \( \theta_2 \) | \( \theta_3 \) | \( \theta_4 \) | \( \theta_5 \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| Bottom blowing plume geometry | | | | | | | |
| Lance height | \( r_t \) | \( \theta_1 \) | \( \theta_2 \) | \( \theta_3 \) | \( \theta_4 \) | \( \theta_5 \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |
| \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) | \( \text{mm} \) |

**Note:** Angle in this table indicates clockwise angle between tap direction and top blowing cavity or bottom blowing plume.
4.3.2 | Bath mixing energy

Mixing energy $E_{\text{mix}}$ [W/t] was calculated by the measured mixing time $\tau_{\text{mix}}$ [s] using Equation (11).\(^{22}\)

$$E_{\text{mix}} = \left( \frac{\tau_{\text{mix}}}{540} \right)^{-\frac{1}{0.5}}$$  \hspace{1cm} (11)

4.3.3 | Cavity formation energy

Cavity formation energy $E_{\text{cv}}$ [W/t] is the energy discrepancy between before and after cavity formation, which can be calculated by considering gravitation energy and surface energy. Since the lance height is constant in this study, effect of lance height to the cavity mode as Haas et al\(^ {33}\) reported is not considered. Zhou et al\(^ {34}\) reported that cavity by top blown jet fluctuates and has semi-steady cavity state depth region. Though cavity formation energy would also fluctuate, we considered average cavity profile in relatively longer experimental time period. In this study, cavity shape for energy calculation was carried out based on Equation (12).\(^ {14}\)

$$E_{\text{CV}} = \left\{ n(\rho_l - \rho_g)gh_{cg}V_c + n(\sigma_i \Delta A/V_c \cdot V_c) \right\} \frac{1}{W \cdot t}$$

$$= \left\{ (\rho_l - \rho_g)g \left( 1 - \frac{1}{\sqrt{2}} \right) H_c + (2\sigma_i H_c/R_c^2) \right\} \cdot \frac{n V_c}{W \cdot (nV_c/Q_T)}$$

$$= \left\{ (\rho_l - \rho_g)g \left( 1 - \frac{1}{\sqrt{2}} \right) H_c + (2\sigma_i H_c/R_c^2) \right\} \cdot \frac{Q_T}{W}$$  \hspace{1cm} (12)

Here, $\rho_l$ is density of bath [kg/m\(^3\)], $\rho_g$ is density of gas [kg/m\(^3\)], $h_{cg}$ is depth of center of gravity [m], $\Delta A$ is surface area change by cavity formation, $H_c$ is cavity depth [m], $\sigma_i$ is surface tension of bath [N/m], $R_c$ is radius of cavity [m], $V_c$ is cavity volume [m\(^3\)], $n$ is number of nozzle holes, $W$ is weight of bath [t], $t$ is time required for gas inside cavity to be replaced [s], and $Q_T$ is top blowing rate [Nm\(^3\)/s].

4.3.4 | Spitting energy

Figure 14 shows the calculated bath vibration energy $E_{\text{vib}}$, bath mixing energy $E_{\text{mix}}$ and cavity formation energy $E_{\text{cv}}$ with different bottom tuyere configurations. The dotted line in Figure 14 means the input energy $E$ in these experiments. The sum of $E_{\text{vib}}$, $E_{\text{mix}}$, and $E_{\text{cv}}$ is smaller than the input energy $E$. Therefore, assuming energy conservation, energy for spitting $E_{\text{sp}}$ (W/t) can be expressed as shown in Equation (13).

$$E_{\text{sp}} = E - (E_{\text{vib}} + E_{\text{mix}} + E_{\text{cv}})$$  \hspace{1cm} (13)

Input energy $E$ is calculated from input energy from top blowing and bottom blowing,\(^ {24}\) and was calculated by the following Equation (14).

$$E = E_T + E_B$$

$$= \frac{0.632 \times 10^{-6}}{W} \cos \theta \cdot \frac{F_T^3 \cdot M}{n^2 d_e x} + 6.18 \frac{F_B \cdot T_l}{W} \cdot 2.3 \log \left( \frac{P_2 + \rho_l L_0}{P_2} \right)$$  \hspace{1cm} (14)

Here, $W$ is weight of bath [t], $\theta$ is tilting angle of nozzle [°], $F_T$ is top blowing rate [Nm\(^3\)/min], $M$ is molecular weight of the gas, $n$ is number of nozzles, $d_e$ is diameter of the nozzle end [m], $x$ is lance height [m], $F_B$ is bottom blowing rate [Nm\(^3\)/min], $T_l$ is temperature of the bath [K], $P_2$ is pressure of atmosphere [kg/m\(^3\)], $\rho_l$ is density of bath [kg/m\(^3\)], $L_0$ is bath depth [m].
Figure 15 shows the relationship between $E_{sp}$ and $R_{sp}$ and indicates that there is a proportional relationship. $E_{sp}$ can be considered as shown in Equation (15).

$$E_{sp} \propto R_{sp} \left( \frac{3}{2} \frac{1}{r} \sigma_1 + gh + \frac{1}{2} v^2 \right)$$  \hspace{1cm} (15)$$

Here, $r$ is radius of spitting droplet [m], $\rho$ is density of water [kg/m$^3$], $h$ is height of spitting capturer above bath level [m], and $v$ is velocity of spitting droplet at capturer height $h$ [m/s]. The first term in Equation (15) is the surface energy change by droplet formation, the second term is the potential energy change by a water droplet traveling from the bath.
surface to the capturer height \( h \) and the third term is the kinetic energy of the droplet at the capturer height \( h \). Although the values of \( r \) and \( v \) were not measured in this study, the fact that the spitting rate \( R_{sp} \) has a proportional relationship with spitting energy \( E_{sp} \), as shown in Figure 15, indicates that \( r \) and \( v \) did not vary significantly among the conditions of this study.

Thus, this study confirmed that, even under a constant top blowing condition and constant energy input, the configuration of the bottom tuyeres and the interference between the top blown gas jet and the bottom blowing plume influence energy distribution and spitting behavior.

5 | CONCLUSION

The effects of top and bottom blowing conditions were investigated by a water model experiment.

1. Under the condition in which only top blown gas was blown, the spitting rate was explained well by the kinetic energy of the top blown gas jet.
2. A numerical calculation indicated that the site of the gas velocity increase near the cavity rim could be the site of spitting generation. The calculation results also indicated that interference between the top blown gas jet and the bottom blowing plume can increase the spitting rate.
3. To quantify the interference between the top blown gas jet and the bottom blown gas plume, a new interference index was proposed. The spitting rate decreased with a lower interference index.
4. The energy distribution in the blowing process was discussed based on the bath mixing time, bath vibration measurements and the spitting rate. The energy for spitting was explained convincingly by the difference between the energy input and the sum of the energy for bath vibration, cavity formation and bath mixing.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

CONFLICT OF INTEREST

The authors have no conflict of interest relevant to this article.

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