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Simulation Analysis of Unified Spot Market Clearing in Southern Region

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ABSTRACT
Numerical simulations are performed to study the characteristics of thermo-acoustic oscillation of a gas confined in a loop-type pipe with the section of short and narrow channels. In order to simulate the irreversible heat exchange between the gas and the pipe wall, the compressible mass, momentum and energy conservation equations are solved in the loop pipe as well as the heat conduction equations in the pipe wall. Spontaneous oscillations are obtained when the temperature gradient along the narrow channel becomes large. It is found that the onset temperature of simulated thermo-acoustic oscillation agrees with that of the stability analysis and increases when the effect of gravity is not taken into account.

1. INTRODUCTION

Thermo-acoustic oscillation is induced when a gas is confined in a pipe with the section of short and narrow channels and the temperature gradient along the narrow channel is large. This phenomenon was known as the production of sound by heat [1], and experiments and theoretical works have been performed and reviewed [2,3]. The thermo-acoustic oscillation by heat is due to the irreversible heat exchange between the gas and the channel wall, and the thermal energy is converted to the kinetic energy of gas oscillation. Mechanical moving elements and electricity are not necessary, and the thermo-acoustic power generation and refrigerators were studied as the application [4,5]. The configuration of flow channel, gas species, and operating conditions have been discussed, and the stability analysis was performed to obtain the threshold of oscillation [6]. In the nuclear engineering field, the thermo-acoustic sensor was proposed to monitor the nuclear reaction [7]. Large temperature difference is widely seen in the nuclear power plant, and various application of thermo-acoustic oscillation might be possible.

In this study, numerical simulations are performed to study the characteristics of thermoacoustic oscillation for nuclear application. A loop-type pipe with the section of short and narrow channels is analyzed, and the simulated results are compared with the theoretical and experimental results [6]. The effect of gravity is also discussed.

2. NUMERICAL SIMULATION

The loop pipe with narrow channels is shown in Figure 1. The size and configuration are almost the same as those used in the experiment [6]. The loop pipe is vertically oriented, and the diameter and the length of the pipe are 0.04 m and 2.8 m, respectively. The loop has a rectangular configuration, and one side of the loop is 0.7 m as shown in Figure 1. A honeycomb-shape flow section called stack, which is a bundle of narrow channels, is included in the loop pipe at the left bottom of a vertical section. The stack length is 0.035 m, and the narrow channel diameter is 0.7 mm. The porosity of the stack, which is the ratio of the cross-sectional flow area between the bundle of narrow channels and the loop pipe, is 0.67. The top of the stack is kept at high temperature by the hot heat exchanger, and the bottom is kept at low temperature by the cold heat exchanger. The length of the hot and cold heat exchangers is 0.013 m. The working fluid is air, and the loop pipe, heat exchangers and stack are all made from stainless steel. The wall thickness of all components is 0.5 mm.

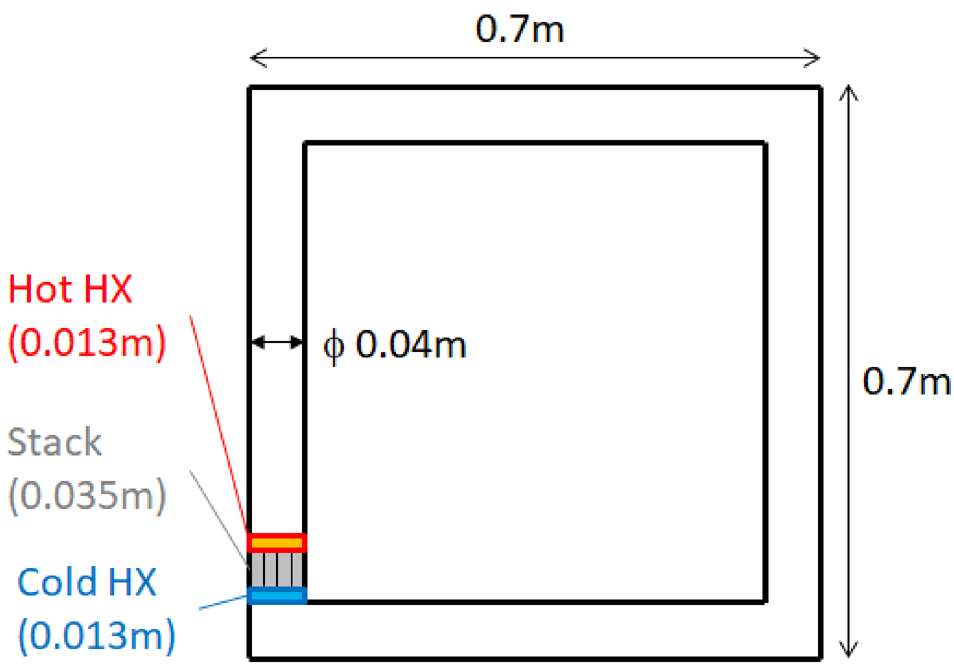

Figure 1: Loop pipe with narrow channel section.

The gas flow in the loop pipe is described by one-dimensional mass, momentum and energy conservation equations along the loop pipe, and the temperature in the pipe wall is calculated by the heat conduction equation. These governing equations are numerically solved using the RELAP5 code [8]. The RELAP5 code is designed to calculate the fluid behavior and structural temperature in nuclear power plants.

One and three-dimensional solvers are implemented in the code, and one-dimensional solver is used in this study. Compressible equations are used in the code since the range of temperature and pressure is very wide in nuclear power plants. Several gases and liquids including air as well as water and steam can be calculated. The finite difference method is used, and the staggered mesh system and the semi-implicit scheme are applied, respectively, for the spatial discretization and the time integration. The number of mesh cells is 60 and the minimum time step size is 0.025ms in this study.

In the numerical simulations, the steady-state flow field without oscillation is established before the onset of thermo-acoustic oscillation. The initial temperature is 295 K for the gas and the pipe wall. The outside temperature of hot heat exchanger is set equal to 455 K at time zero, while that of cold heat exchanger and pipe wall is unchanged. The heat transfer coefficient is 5 W/(m^2K) for inner and outer surface of the pipe wall. After the steady-state flow field in the gas and temperature field in the pipe wall are established, the heat transfer coefficient in the stack is increased to simulate large heat transfer in the narrow channel. The temperature of hot heat exchanger is then slightly increased to make the temperature gradient along the stack large.

3. RESULTS AND DISCUSSION

3.1. Steady-State Flow Field

The variations of flow velocities, pressures and temperatures at four locations in the loop pipe up to the steady state are shown in Figures 2, 3 and 4, respectively. The selected locations are the stack mid elevation, top left, top right and bottom right in the loop pipe shown in Figure 1, and the upward flow in the stack is defined as the positive direction. The circulating flow in the positive direction is calculated as shown in Figure 2, and the steady-state flow field is shown to be established after about 1000 s. The velocity in the stack is larger than that in the other part of the loop pipe, since the flow area is smaller, and the temperature is higher in the stack. The pressure distribution shown in Figure 3 corresponds to the elevation change. The pressure at the top of the loop pipe is lower than that at the bottom due to the gravity, and the stack pressure is slightly lower than the bottom pressure. The temperature distribution is shown in Figure 4, where the steady-state temperature distribution is established after about 1000 s. The temperature is higher in the stack and decreases along the loop pipe in the positive direction. The bottom right temperature is the same as the cold heat exchanger temperature, and it is shown that the loop pipe is cooled by environment. It is confirmed from these figures that the steady-state flow field is established up to 2000 s.

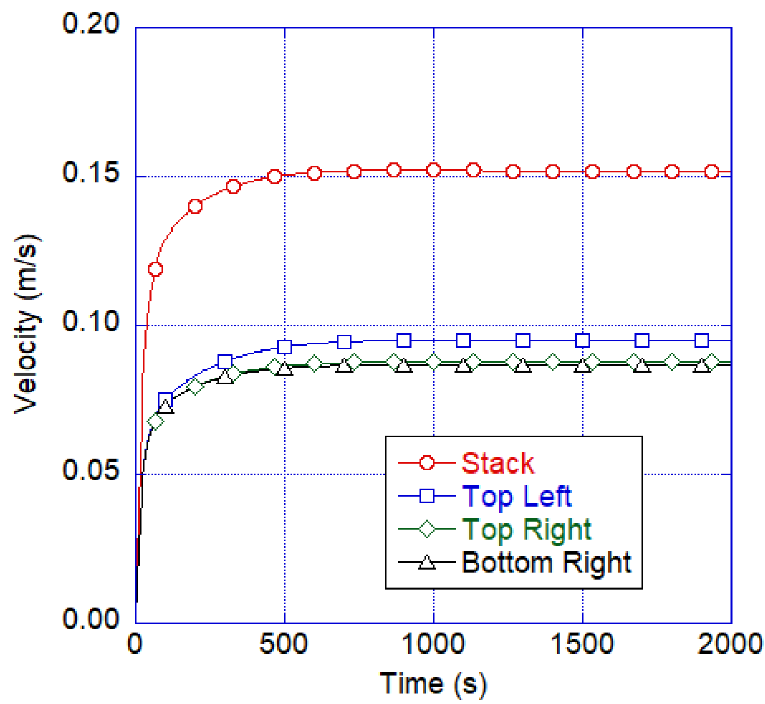

Figure 2: Velocity variation up to the steady state.

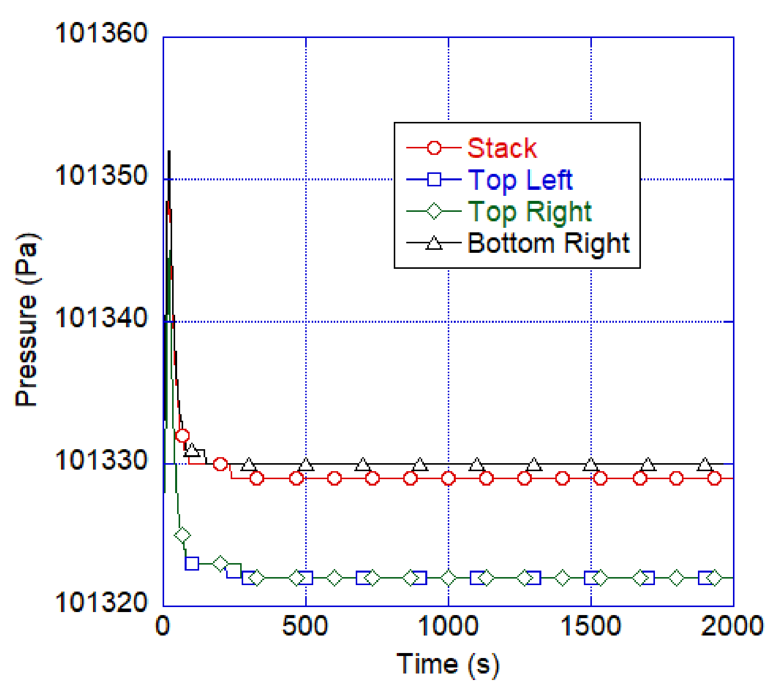

Figure 3: Pressure variation up to the steady state.

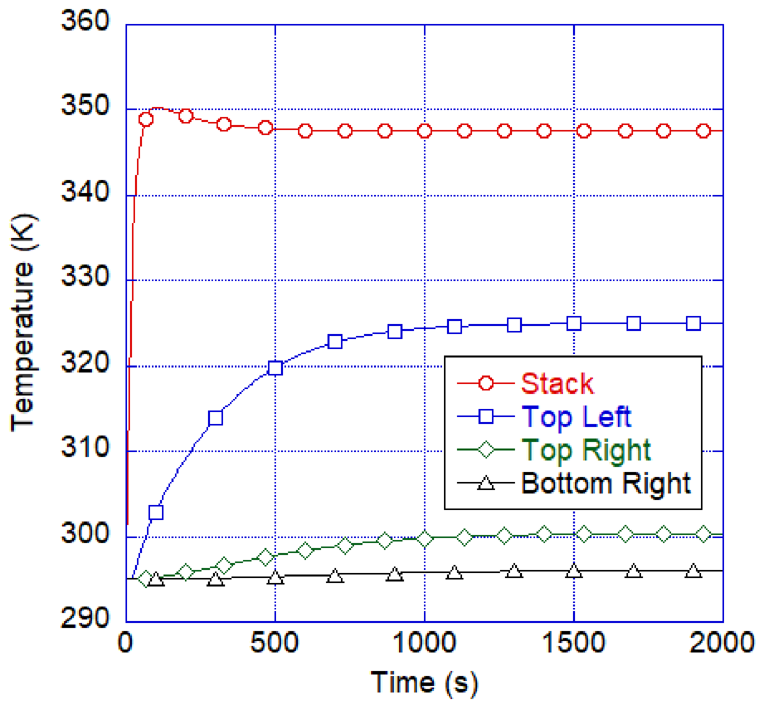

Figure 4: Temperature variation up to the steady state.

3.2. Spontaneous Oscillation

After the steady state is established in the loop pipe, the heat transfer coefficient in the narrow channels is increased to 200 W/(m^{2}K) at 2000 s. The flow velocity shown in Figure 2 and the temperature in Figure 4 increase slightly after the heat transfer coefficient is increased, and the stable circulating flow in the positive direction is calculated again. The temperature of hot heat exchanger is then increased slightly. The velocity variation is shown in Figure 5 when the temperature of hot heat exchanger is increased to 475 K at 2000 s simultaneously with the heat transfer coefficient. A large oscillating flow is calculated spontaneously at about 2020 s, and the amplitude of oscillation is much larger than the steady-state flow velocity. It is noted that such a spontaneous oscillation is not calculated when the temperature of hot heat exchanger is below 470 K. This indicates that there are some threshold values for the temperature of hot heat exchanger and the temperature gradient in the narrow channel. The pressure variation is shown in Figure 6. A large pressure oscillation around the steady-state pressure is also seen corresponding to the velocity oscillation. The temperature variation is shown in Figure 7, where small oscillations are indicated around some average temperatures. After the onset of oscillation, the stack temperature increases, and the top left and top right temperatures decrease slightly. This indicates that mixing is enhanced in the stack and loop pipe due to the oscillation.

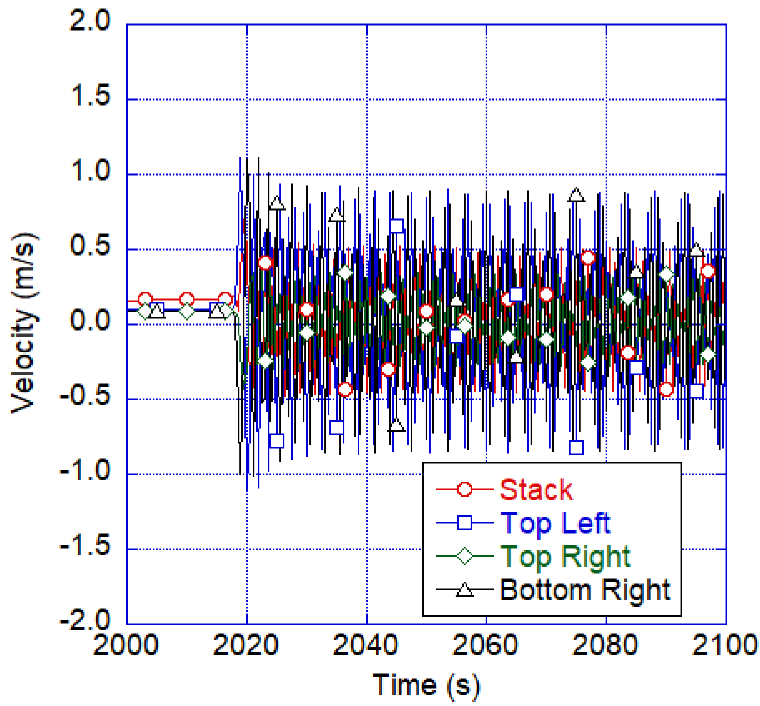

Figure 5: Velocity variation after the steady state.

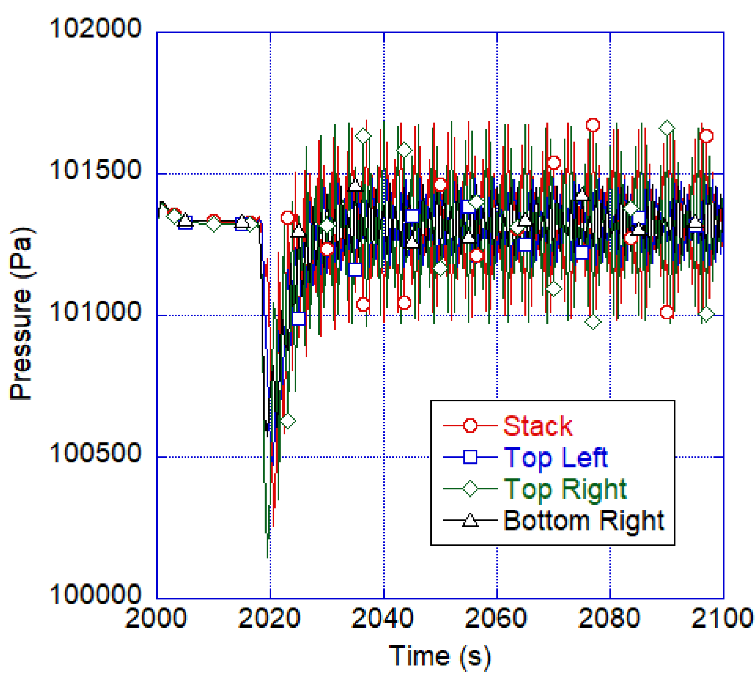

Figure 6: Pressure variation after the steady state

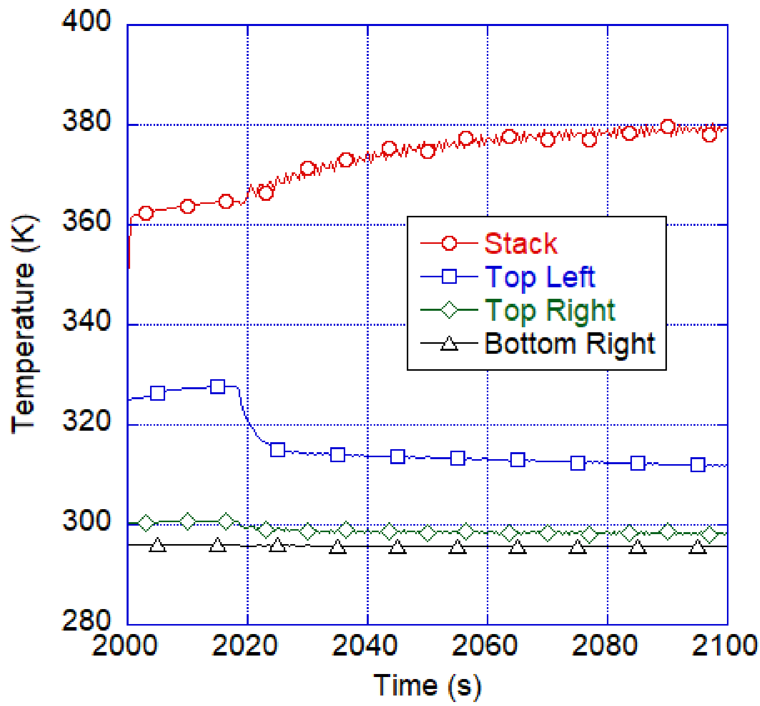

Figure 7: Temperature variation after the steady state.

3.3. Sound Speed and Amplitude

The velocity, pressure and temperature variations for 0.01s after 2100s are shown in Figures 8, 9 and 10, respectively. The temperature variation in Figure 10 is obtained as the variation of temperature difference between the local average temperature and the oscillating temperature. It is found in Figures 8-10 that the oscillation period is the same in the stack and the other locations of the loop pipe. The oscillation period is about 0.008s, and the sound speed is estimated to be 350 m/s. This sound speed corresponds to the average temperature of 304 K for the adiabatic sound speed and to 427 K for the isothermal sound speed. The outside temperatures of cold and hot heat exchangers are set at 295 K and 475 K, respectively, and the sound speed of oscillation is shown to be in this temperature range.

The amplitude of velocity oscillation in Figure 8 is shown to be larger for the top left and bottom right locations, while smaller for the stack and top right locations. On the contrary, the amplitude of pressure oscillation in Figure 9 is larger for the stack and top right locations, while smaller for the top left and bottom right locations. This tendency is the same for the temperature oscillation shown in Figure 10, though the phase of stack temperature is shifted. The stack is at about the bottom left location, and the top right location corresponds to the half of the wavelength from the stack. The oscillation amplitude is shown to be affected by the location in the loop pipe.

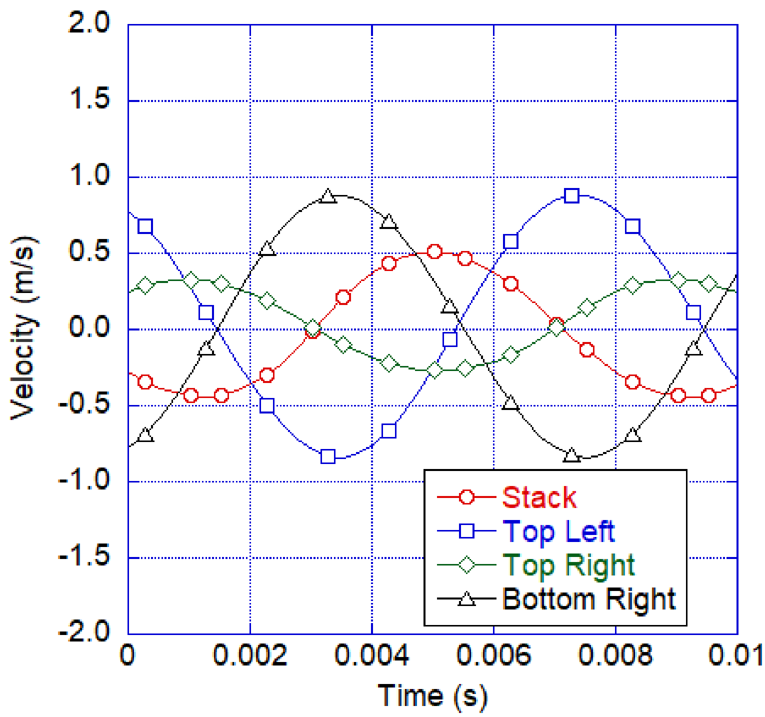

Figure 8: Velocity oscillation for 0.01s after 2100s.

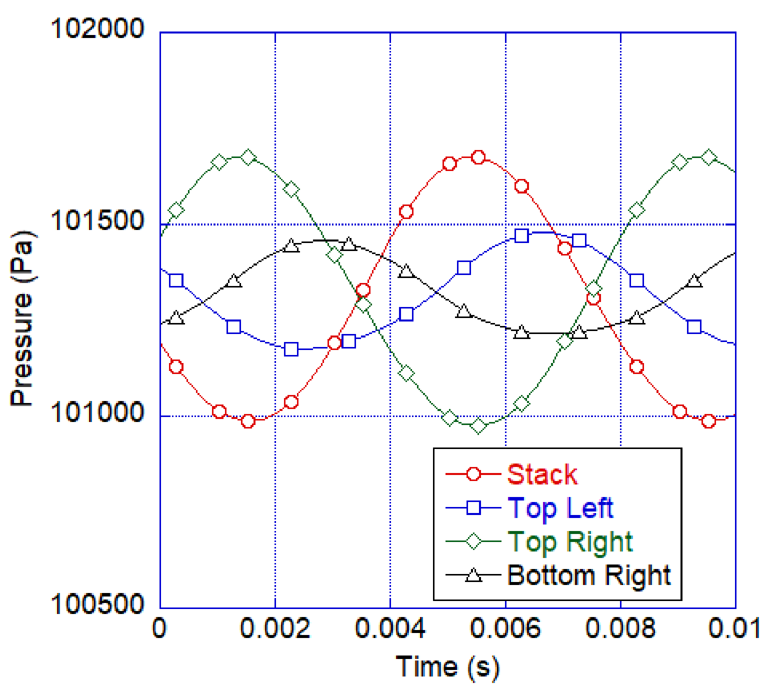

Figure 9: Pressure oscillation for 0.01s after 2100s.

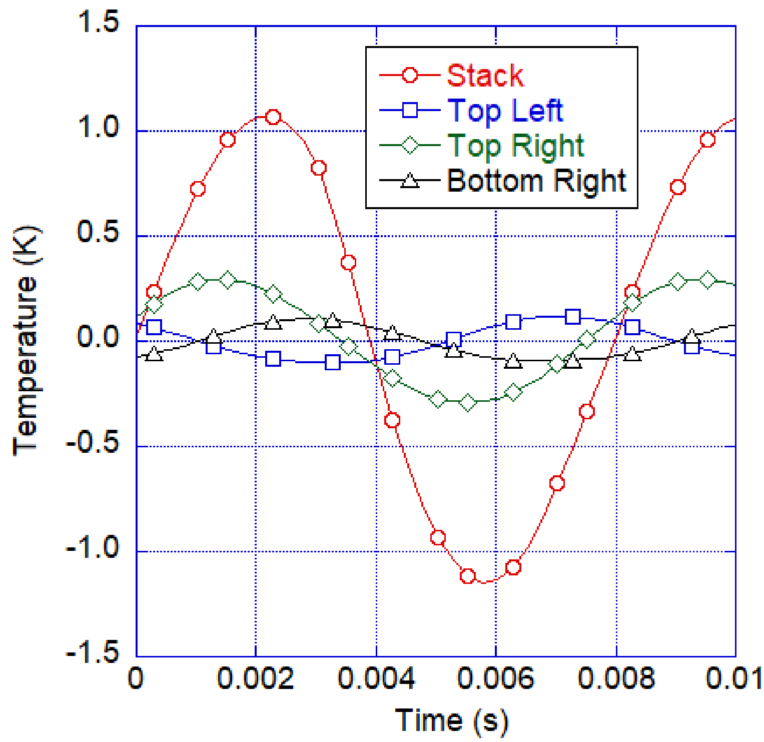

Figure 10: Temperature oscillation for 0.01s after 2100s.

3.4. Onset Condition

The spontaneous oscillation was calculated when the temperatures of hot and cold heat exchangers were 475 K and 295 K, respectively, in the above simulation. The threshold temperature of hot heat exchanger is about 475 K, since the oscillation was not observed at 470 K. The threshold temperature is evaluated using the temperature ratio between the hot and cold heat exchangers, Th and Tc [6]. This threshold value is also called stability limit. The threshold temperature ratio is a function of the oscillation parameter $\omega\tau$, where ω is the angular frequency of oscillation and τ is the thermal relaxation time defined by $r^2/(2\alpha)$, where r and α are, respectively, the radius of narrow channel and the thermal diffusivity. In this study, the radius of narrow channel is 0.35 mm, but varied from 0.1 mm to 0.8 mm here to change the parameter value, and the threshold temperature of hot heat exchanger is obtained keeping the other conditions unchanged. The threshold temperature ratio is shown in Figure 11 as a function of the oscillation parameter, where the analytical results and experimental data [6] are also shown. The present calculation is based on the experimental condition [6] and the obtained temperature ratio agrees well with the experiment and the analysis. It is found that the present numerical simulation represents well the thermo-acoustic oscillation in the loop pipe shown in Figure 1.

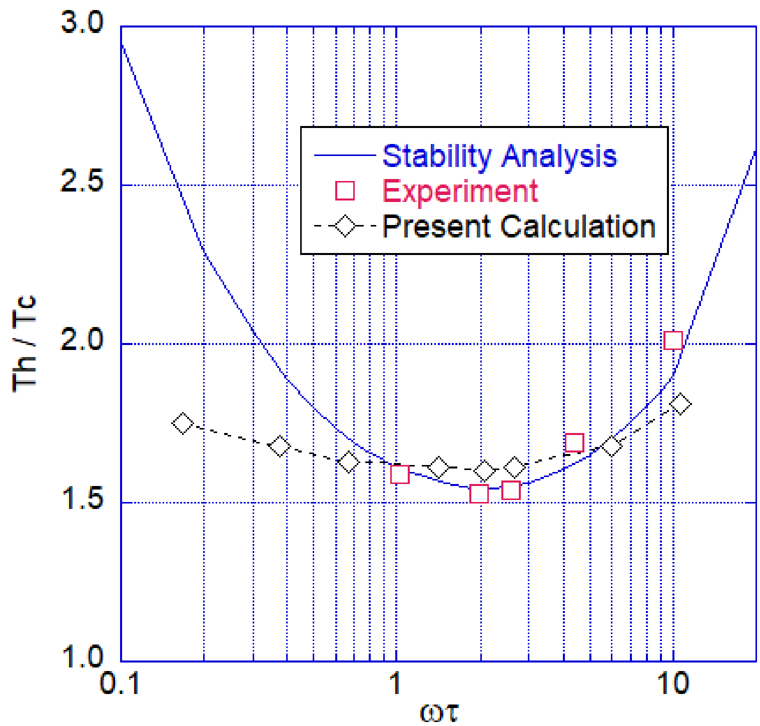

Figure 11: Stability condition of spontaneous oscillation.

3.5. Effect of Gravity

In the above simulation, the loop pipe is vertically oriented as shown in Figure 1. The heated air goes up from the hot heat exchanger and the steady state circulating flow and temperature distribution are established due to the gravity as shown in Figures 2-4. The effect of gravity is discussed here by setting the gravitational acceleration equal to zero. This case study corresponds to the horizontally oriented loop pipe, or the loop pipe used in the zero-gravity space. In the following simulation, the steady-state calculation for 2000 s is initially performed as was the case with the gravity. The calculated steady state is shown in Figures 12-14, where the velocity is zero, the pressure is the same in the loop pipe up to 2000 s, and the gas temperature increases in the stack alone and the other temperatures are the same as the initial value. This is because the gravity is only the driving force for the circulating flow. It is thus confirmed that the circulating flow with temperature distribution is formed by the gravity. It is noted that no spontaneous oscillation is observed after this zero-flow steady state even if the heat transfer coefficient is increased to 200 W/(m^{2}K) and the temperature of hot heat exchanger is increased to 600 K, while 475 K was the threshold temperature for the case with the gravity.

The effect of steady-state temperature distribution is studied in the following. The hypothetical flow velocity of 0.095 m/s, which is the velocity obtained with the gravity as shown in Figure 2, is applied at the top left position for 100 s after 2000 s to establish the temperature distribution in the loop pipe. The heat transfer coefficient in the stack and the temperature of hot heat exchanger are increased to 200 W/(m^{2}K) and 475 K, respectively, as was the case with the gravity. The resulting flow field is shown in Figures 12-14 from 2000 s to 2100 s. It is found that the circulating flow field with the temperature distribution is obtained but no oscillating flow is calculated. The hypothetical flow velocity is not applied after 2100 s, and the temperature of hot heat exchanger is increased. It is confirmed by several trial calculations that the oscillating flow is calculated after 2100s but damped when the temperature of hot heat exchanger is below 555 K. The case with 555 K is shown in Figures 12-14, where the oscillating flow appears after 2100 s. The oscillation seems to be damped up to about 4000 s, but continues to 6000 s. The threshold temperature is thus about 555 K, and the temperature ratio is 1.88. This threshold temperature ratio is much higher than that in the case with the gravity shown in Figure 11. The threshold temperature ratio is reported to be affected by the temperature distribution in the loop pipe [6]. It is found that the threshold temperature ratio for the stability limit is reduced due to the gravity and the thermo-acoustic oscillation occurs with smaller temperature gradient. This indicates for the application of thermo-acoustic oscillation that the vertical orientation is of advantage and larger temperature ratio is necessary for the space utility than for the ground application.

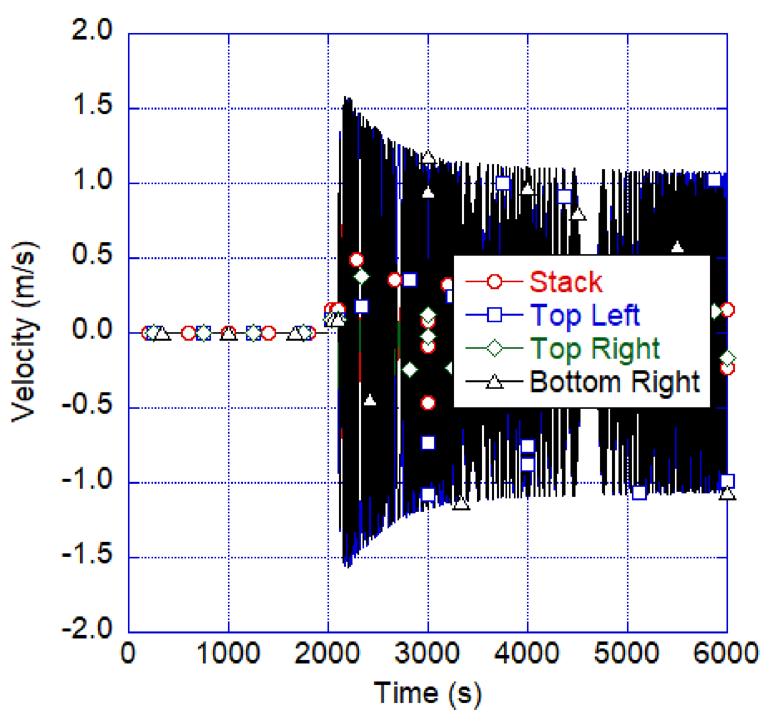

Figure 12: Velocity variation in case of zero gravity.

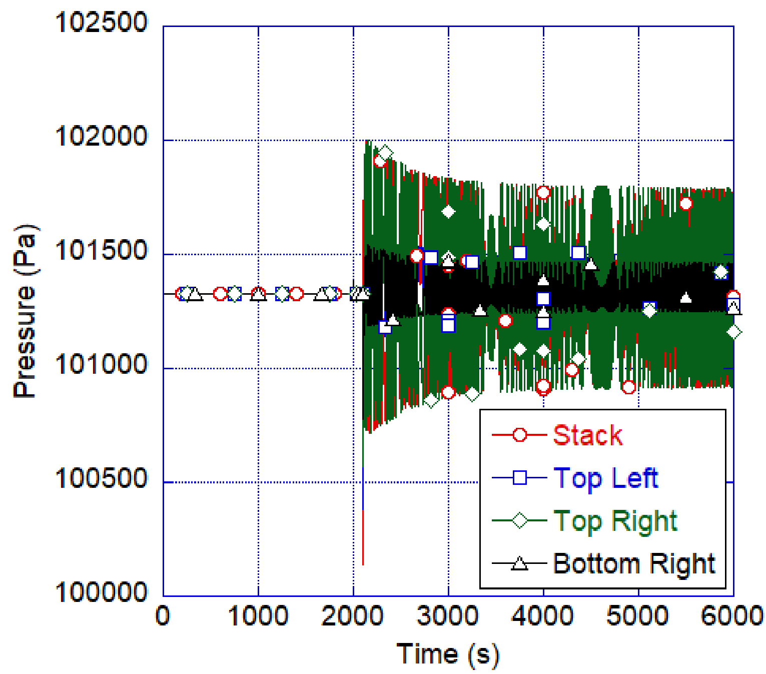

Figure 13: Pressure variation in case of zero gravity.

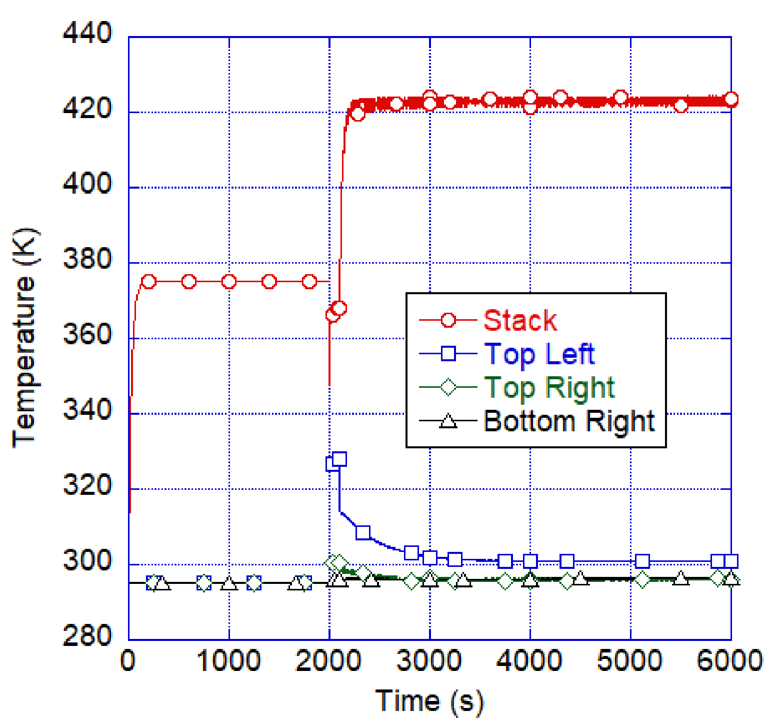

Figure 14: Temperature variation in case of zero gravity.

4. CONCLUSION

The thermo-acoustic oscillation of air in the loop pipe has been numerically simulated by solving the one-dimensional compressible mass, momentum and energy conservation equations and the heat conduction equations in the pipe wall. Spontaneous oscillations were obtained when the temperature gradient along the narrow channel becomes large. The oscillation amplitude was shown to be affected by the location in the loop pipe. The onset condition of simulated thermo-acoustic oscillation was shown to agree with that of the stability analysis. The temperature distribution in the loop pipe by the circulating flow due to the gravity was found to play an important role for the thermo-acoustic oscillation, and the threshold temperature increased when the effect of gravity was not taken into account. From the viewpoint of nuclear application, the vertical orientation is of advantage for the loop-type pipe and higher threshold temperature would be necessary for the space utility than for the ground application.

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