

A Numerical Study on Jet Structure and Noise Emission of Underexpanded Radial Jet

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Abstract

In this study, an underexpanded radial jet issuing from a small gap between two circular tubes facing each other is investigated numerically. Radial jet is formed, for example, downstream of high-pressure valves in piping system and of poppet valves in engines, and causes many industrial problems such as the noise generation and the fatigue failure of structure. In this study, the jet issuing from a small gap between two tubes with same diameter is numerically simulated. The flow field is assumed to be axisymmetric against the central axis of tubes and to be symmetric against the intermediate plane between the exits of two tubes. The axisymmetric Euler equations are solved using symmetric TVD (Total Variation Diminishing) scheme. The effects of nozzle pressure ratio and of diameter of circular tubes on the structure and the behavior of jets are examined. Typical cell structure of underexpanded jet appears in radial jet and the length of cell becomes smaller in downstream region because the jet spreads radially like a disc. The length and width of first cell are larger with higher nozzle pressure ratio. Many vortices are generated one after another near the jet boundary and move downstream, which cause the oscillation of jet. Outside of jet, two types of density waves are observed. One of them propagates toward the nozzle (toward the upstream region) and the other propagates in opposite direction. Focusing on the pressure change caused by the former waves, which is related to well-known screech, dominant frequency obtained by FFT analysis was found to become lower with higher pressure ratio and smaller diameter of tube.

Keywords

Compressible Flow, Screech, Oscillation, Underexpanded Jet

1. Introduction

Supersonic jet is used in various industrial scenes, such as an assist gas to remove molten material in laser processing [1], a cooling jet in glass tempering process [2] and so on. The jet issuing from a convergent nozzle becomes underexpanded when the pressure ratio across the nozzle is higher than the critical pressure ratio (about 1.893 in case of the air). The underexpanded jet has typical cellular structure in barrel shape, which consists of the alternate expansion and compression regions. Shock waves appear in such a cell structure. Powell [3] reports the screech sound caused by the interaction between these shock waves and the disturbances traveling around the jet. It is well known that the screech is the narrow-band noise with high frequency and it has multiple modes. Tam [4] examined the generation mechanism and the direction of screech in case of the jet issuing from a circular nozzle. And it has shown that the Mach number and the size of cell affect the characteristics of the screech, by comparison with Norum's experimental results [5]. Besides, so far, two-dimensional rectangular jets and axisymmetric jets have been studied by many researchers concerning jet structure, oscillation phenomena, noise generation and so on [6]-[11].

The present study focuses on the underexpanded jet which is radially discharged into the atmosphere. The radial jet issuing from a small gap between two circular tubes facing each other is numerically investigated and the flow characteristics are shown, such as the jet structure and the relation between oscillation phenomena and noise emission. The radial underexpanded jet is formed, for example, downstream of valves in high-pressure piping system and of poppet valves in engines. Also the wall jet of impinging jet has similar structure when axisymmetric supersonic jet impinges on a flat plate. In such flow field, the oscillation of jet and the noise generation cause some problems in industrial point of view [12].

2. Numerical Scheme

To examine the characteristics of underexpanded radial jet in this study, the flow field that Kawasaki [13] experimentally studied is simplified and it is devised as a computational model as shown in **Figure 1**. Two circular tubes each fitted to a high pressure tank, are installed face to face each other. The airflows through tubes collide with each other on the intermediate plane between two tubes, change their directions and radially spread out into the atmosphere from a gap of tubes. The inside wall of each tube near the gap is designed for the air to reach the sonic speed at the exit of gap. In the figure, the shapes of jet on the cross sections along seven radial directions are drawn with black dashed line as examples. The computational model is more simplified, so that the flow field is assumed to be symmetric against the intermediate plane between two tubes and to be axisymmetric against the centerline of tube.

Figure 2 shows the computational model used in this study, which corresponds to the region surrounded by a red dotted line in **Figure 1**. The central axis

of tubes is taken as x -axis, and y -axis is taken to be normal to x -axis as shown in this figure. The origin of this coordinate system is on the intermediate plane between tubes. Because of the symmetric conditions as mentioned above, only the positive region of y is taken as the computational domain. The jet is exhausted from gap b into the atmosphere at speed of sound. Therefore, the critical conditions are applied to the nozzle exit as the boundary conditions. The outer wall of the tube is the slip wall and the symmetric conditions are given on the left-side boundary of computational domain. Because the upper-side and the right-side boundaries are located in the atmosphere, the atmospheric pressure is given and the velocity and the density are calculated using the method of characteristics on the boundaries.

Computational parameters are shown in **Table 1**. In this study, two types of circular tube are used. Outer diameter of the one is $D = 12$ mm and that of the other $D = 16$ mm. The gap between the tubes $b = 2$ mm is fixed. Compressed air from two tubes collides with each other, changes the direction and issues from the gap into the atmosphere. In this study, the nozzle, which consists of two tubes, discharging the underexpanded jet is called “slit nozzle”.

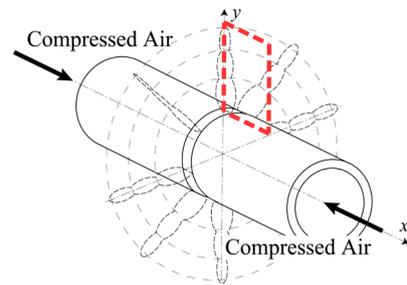


Figure 1. Slit nozzle.

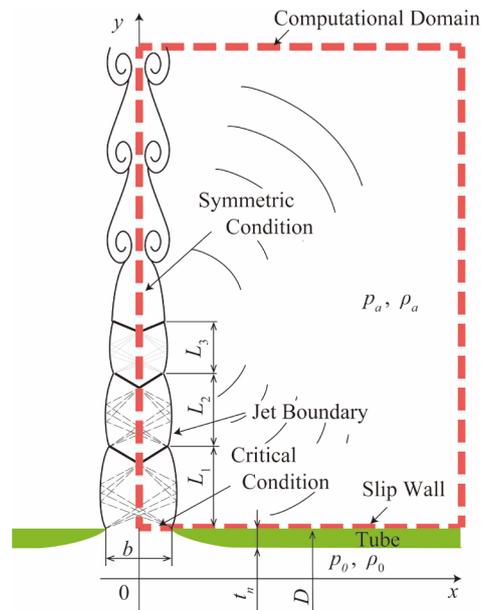


Figure 2. Computational model.

Table 1. Computational parameters.

Outer diameter of tube D	12 mm, 16 mm
Nozzle width b	2 mm
Tube thickness t	1 mm
Pressure Ratio PR	2.0 - 6.0

The region surrounded by a red dashed line in **Figure 2** is the computational domain. 300 computational grids are uniformly taken between $x/b = 0.0$ and 7.5 in x -direction and 600 grids between nozzle exit and $y/b = 15.0$ are taken in y -direction. The grids outside of this uniform region become coarser both in x - and y -directions as further away from the origin. The maximum value of computational area is $x/b = 11.0$ and $y/b = 49.5$. The jet is exhausted from lower left of computational domain, and the air flows toward the upper side of the figure. Pressure ratio PR which is the ratio of the pressure in high pressure chamber p_0 and the atmospheric pressure p_a is changed between 2.0 to 6.0.

As mentioned above, the flow field is assumed to be axisymmetric against x -axis, and to be symmetric against the intermediate plane between two tubes. Therefore, the axisymmetric Euler equations are solved using our in-house program with the symmetric TVD (Total Variation Diminishing) scheme [14], which has second order accuracy both in space and time and has been shown to work well on the analysis of the impinging-jet simulation [15].

3. Results and Discussion

3.1. Pressure and Density Contours

Figure 3 show the instantaneous jet structure obtained by numerical simulation. The jet is exhausted from the nozzle exit in the bottom of the figure. Outer diameter of slit nozzle is $D = 12$ mm. The left half of figure shows the pressure contours and the right half the density contours.

In **Figure 3(a)**, two barrel-shaped cells are formed just downstream of nozzle exit and the vortices dominate in the downstream region. The width and the length of second cell are found to be smaller than those of first cell. This is conspicuous feature of radial jet because the jet spreads radially and then, decrease ratio of the neighboring cell sizes is larger than that of the rectangular jet and the axisymmetric jet. In **Figures 3(b)-(d)**, the similar jet structure is found, while the length of first cell becomes larger at higher pressure ratio.

Surrounding the jet, two types of density waves can be observed. One of them propagates toward the nozzle (toward the upstream region) and the other propagates in opposite direction. In case of the jet with $D = 12$ mm, frequency of pressure change at fixed point near the nozzle, which is caused by the density waves propagating upstream, was reported to agree with that of screech tone obtained by experiment [16].

Figure 4 show the instantaneous jet structure with $D = 16$ mm for different PR . Although the jet structure and density waves show the almost same tendency

as those in **Figure 3**, the size of cells is seen to become comparatively large. The radial jet narrows downstream to satisfy the continuity equation, while the rectangular jet does not change the jet width. The smaller the diameter becomes, the more the effect of the diameter on the jet width appears. Therefore, the jet with $D = 12$ mm becomes narrower than that with $D = 16$ mm.

3.2. Cell Length

Figure 5 shows cell length of the jet for each pressure ratio measured from the density contours. L_1 , L_2 and L_3 are the length of first, second and third cell, which are shown in **Figure 2**. The cell length of radial jet becomes longer as pressure ratio becomes higher, this is similar with well-known characteristics of the rectangular jet [17]. Although the cell length of the rectangular jet slightly decreases downstream because of the shearing stress in jet boundary, as notable characteristics of radial jet, the decrease ratio of adjacent cell sizes is higher than that of rectangular jet because of the effect which narrows the jet width as mentioned above. These are confirmed also in **Figure 3** and **Figure 4**.

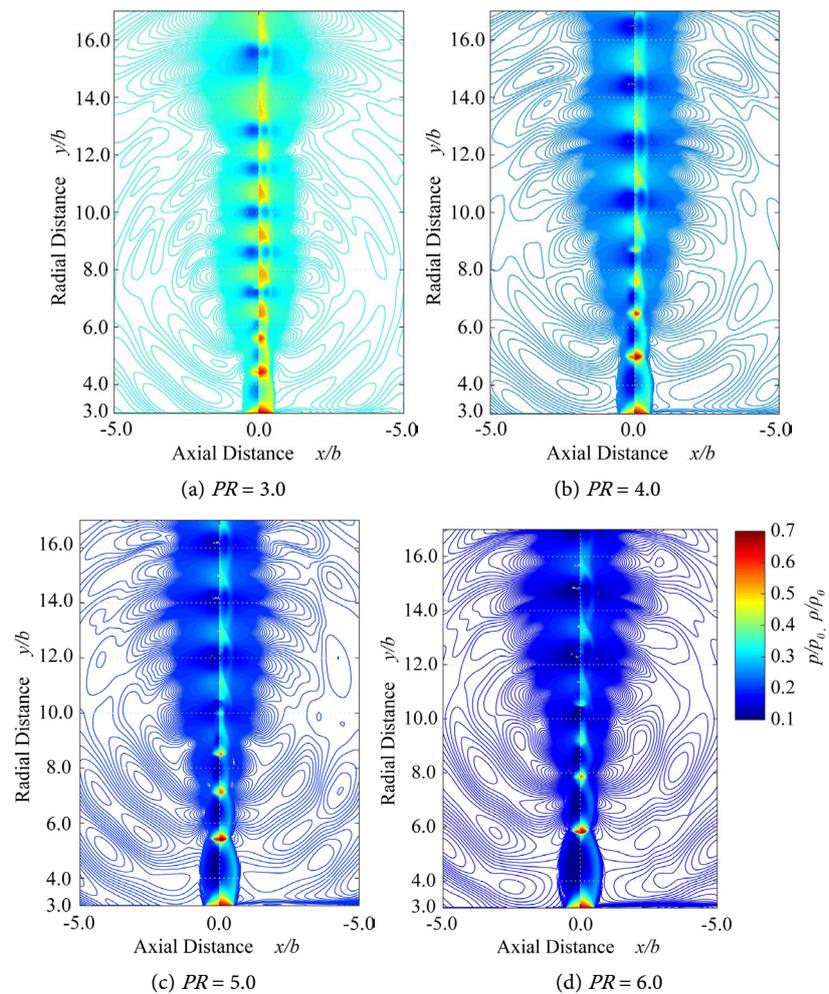


Figure 3. Pressure (left) and density (right) contours of underexpanded radial jet ($D = 12$ mm).

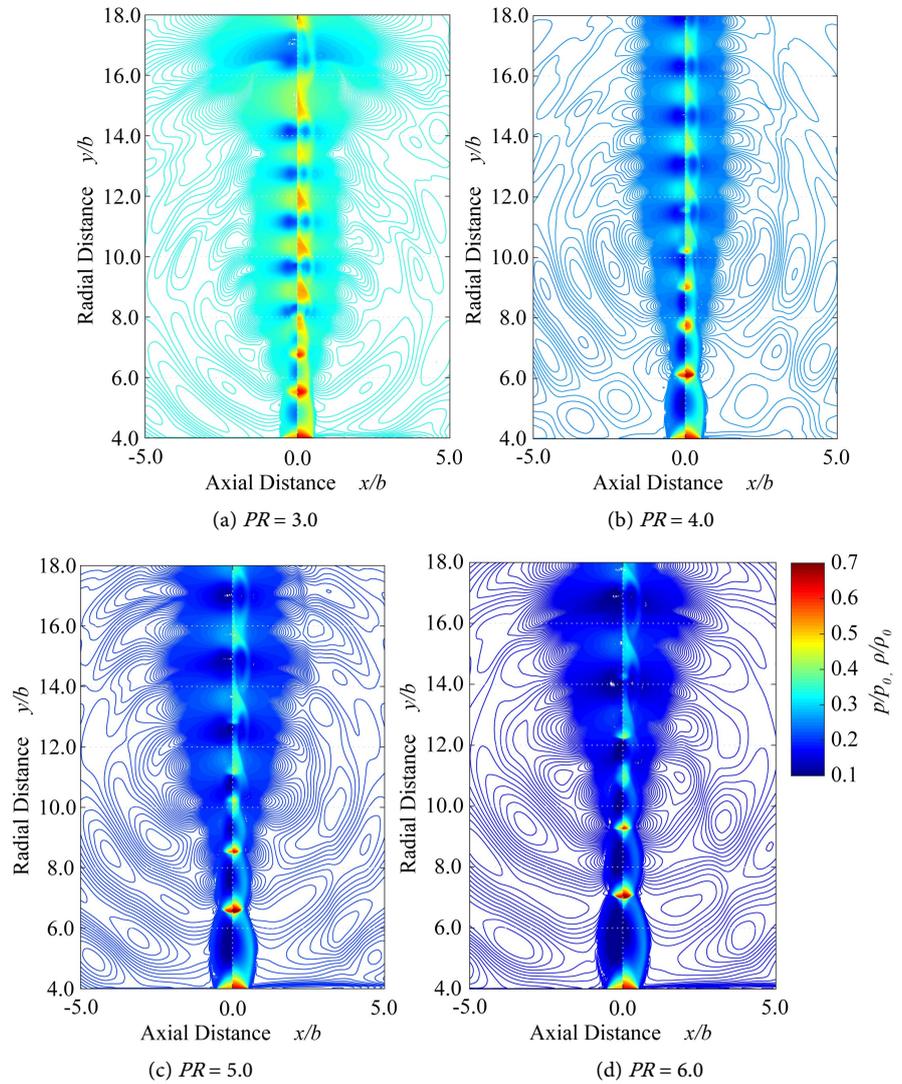


Figure 4. Pressure (left) and density (right) contours of underexpanded radial jet ($D = 16$ mm).

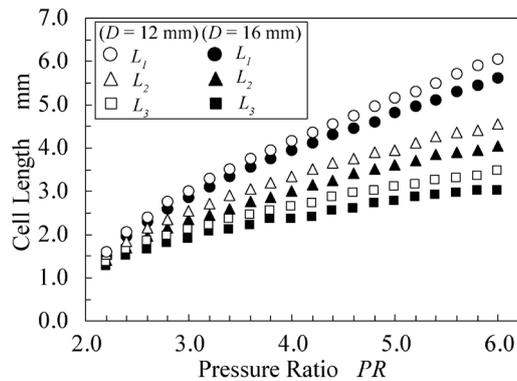


Figure 5. Cell length.

In **Figure 5**, when PR is less than 2.8, cell length gradually increases and, when PR is higher, it becomes larger linearly. Furthermore, as discussed above,

the cell length with $D = 16$ mm is found to be larger than that with $D = 12$ mm because of the effect which narrows the jet width.

3.3. Frequency of Jet Oscillation

Radial jet oscillates periodically with vortices moving downstream. **Figure 6** shows the example of the result of FFT analysis of pressure history recorded at the end of 2nd cell of the jet. This is the result for $D = 12$ mm at $PR = 3.0$. Dominant frequency at about 80 kHz appears, which can be considered to be screech tone because, in **Figure 3**, the cell node of 2nd cell is positioned in the region surrounded by density waves which propagate upstream toward the nozzle.

Figure 7 shows the screech frequency for different pressure ratios. Screech frequency tends to decrease when the pressure ratio increases. And it can be considered that there are several modes in screech frequency because jump to the other mode appears in several places. Such characteristic of the frequency has been reported by many researchers concerning the rectangular jet. And the frequency is well-known to be inversely proportional to the nozzle width. In case of the radial jet as shown in **Figure 7**, as a whole, the frequencies of $D = 12$ mm are larger than those of $D = 16$ mm. In other words, for the radial jet with $D = 12$ mm to have same frequencies as those with $D = 16$ mm, the larger PR is necessary than that of $D = 16$ mm. For example, the frequency with $D = 12$ mm at $PR = 3.2$ is almost equal to that with $D = 16$ mm at $PR = 2.8$. Thus, screech frequency depends on D and PR .

The cell lengths L_1 , L_2 and L_3 at almost same frequency are listed in **Table 2**. This table shows three cases that frequency is almost same. As the first case, the frequency with $D = 12$ mm at $PR = 3.2$ is 78.2 kHz and that with $D = 16$ at $PR = 2.8$ is 79.3 kHz. These frequencies are very close. Under these conditions, although the difference of length L_1 is 0.3, the difference of L_2 is 0.1 and that of L_3 is also 0.1. In the same manner, the frequencies of second case are 66.4 kHz and 67.1 kHz and those of third case are 54.0 kHz and 54.4 kHz. Also in the second and the third case, the difference of L_2 and that of L_3 are 0.1, respectively. Thus, the 2nd or the 3rd cell length is closer than that of 1st cell length in every case. So, it is considered that the screech frequency of jet depends on the length of 2nd or 3rd cell in case of radial jet.

3.4. Directivity of Density Waves

In order to investigate the directivity of the screech of the radial jet, the sound pressure of screech surrounding the jet is also measured. Measurement is performed in a semicircle with 3rd cell end as a center. The radius of the semicircle is the distance between nozzle exit and 3rd cell end. Measurement is carried out at 10 positions stepped by 15 degrees. At every point, the pressure history is analyzed by FFT and screech frequency is obtained like **Figure 6**. The sound pressure of screech is shown as a radar chart in **Figure 8**. The sound pressure

becomes strongest at the position “2”, “3” and “10”. In addition the noise radiation cannot be seen in the direction of 90 degrees. These features are similar to axisymmetric jet [4].

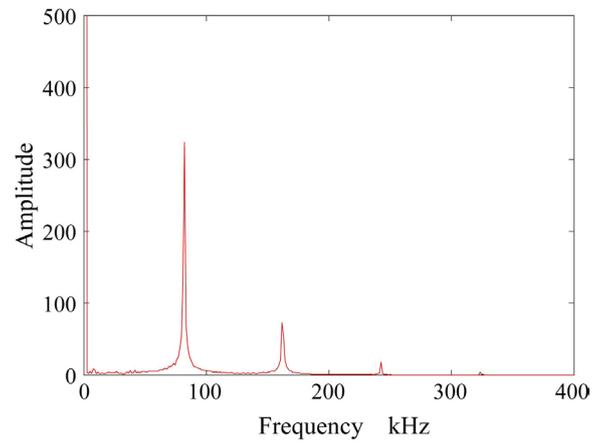


Figure 6. Analysis of pressure oscillation in jet.

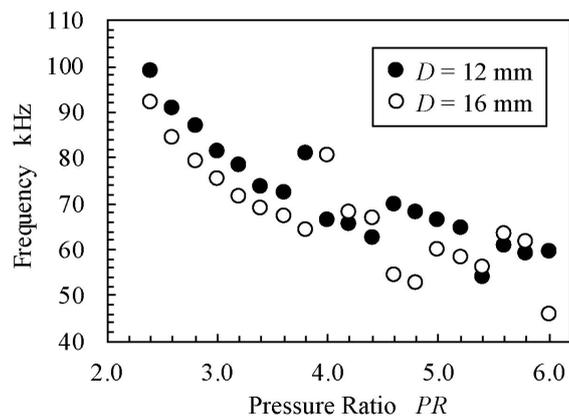


Figure 7. Screech frequency for different PR and D .

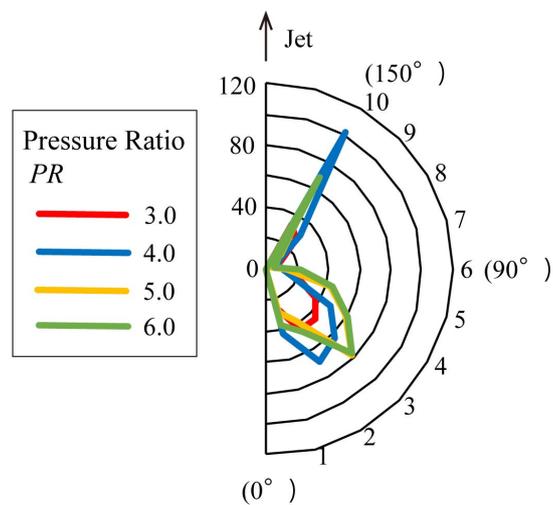


Figure 8. Sound pressure distribution ($D = 12$ mm).

Table 2. Screech frequency and cell length.

D	PR	Frequency	Cell Length mm		
		kHz	L_1	L_2	L_3
12	3.2	78.2	3.1	2.5	2.1
16	2.8	79.3	2.8	2.4	2.0
12	4.0	66.4	4.0	3.0	2.4
16	3.6	67.1	3.8	3.1	2.5
12	5.4	54.0	5.1	3.9	2.9
16	4.6	54.4	4.8	3.8	3.0

4. Conclusions

The underexpanded radial jet is numerically simulated and the flow characteristics of the jet are examined, especially concerning its cellular structure and the relation between the oscillation phenomena and the screech. Thereby, the following conclusions are drawn:

- 1) Cell length of first cell becomes larger with higher pressure ratio and decrease ratio of cell length of radial jet is larger than that of rectangular jet.
- 2) The radial jet issuing from slit nozzle with smaller diameter has higher frequency screech and the frequency decreases with higher pressure ratio.
- 3) Sound pressure of the noise emitted from the radial jet has directivity. Upstream-travelling noise forms screech phenomena.
- 4) Screech frequency mainly depends on the length of 2nd or 3rd cell.

In addition, the computational model presented in this paper can be considered useful for analyzing the behavior of the rectangular jet, because the configuration of jet becomes two-dimensional when the tube diameter tends to infinity. Therefore, to understand the characteristics of the radial jet will become one of clues to clarify those of the rectangular jet which has been studied for many years.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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