

Study of Mechanism of Silencer Drainage Noise

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ABSTRACT

Noise occurring at the exhaust outlet during idling and originating in condensate water accumulating in the silencer reduces the commercial appeal of vehicles. Visualization tests reproducing a silencer and predictive calculations based on a one-dimensional model were conducted in order to elucidate the mechanism of occurrence of this noise and study measures to prevent it. The results showed that pulsative pressure from the engine and the internal resonance of the exhaust pipes were factors in drainage noise, and the noise occurred when water films that had been generated and blocked the outlet pipe in areas in which the particle velocity was highest migrated downstream and broke up.

In addition, in order to prevent drainage noise, increasing the pressure differential before and after the formation of the water film, ΔP , is an effective measure in increasing drainage performance during idling.

1. Introduction

Automotive exhaust systems reach high temperatures due to combusted gases in the engine, and are subjected to conditions of severe thermal shock as a result of the cooling of the exhaust gas by the external air as it proceeds towards discharge. These temperature changes are a factor in the generation of a variety of noises. These noises reduce the commercial appeal of the vehicle, and their amelioration is therefore necessary.

Silencer drainage noise is one of the noises that occur in the exhaust system. The hydrogen component contained in gasoline forms water vapor by bonding with oxygen in the air; cooling of this vapor in the silencer results in the formation of condensate water (termed “water” below) and drainage noise originates from the flow of this water and exhaust gas.

This type of flow field in which gas and liquid are mixed is termed a gas-liquid two-phase flow, and has been the subject of a great deal of research in relation to industrial equipment and facilities such as boilers⁽¹⁾. Shimizu et al.⁽²⁾ explicated the mechanism of the breaking wave phenomenon which occurs when water and air mix in siphon pipes used in water and drainage systems. This research elucidates the phenomenon mainly in the case of transport of liquids. In the case of automotive exhaust pipes, idling over long periods and other use conditions result in considerable water accumulation in the silencer, producing gas-liquid two-phase flows. However, because heat, gas flows, and pulsative pressure from the engine

affect the phenomenon in complex ways, its theoretical analysis is challenging, and troubleshooting is therefore generally based on experience. Today’s use of low exhaust pressures, however, promotes the accumulation of water in the silencer, and drainage noise is becoming increasingly severe.

The research discussed in this paper analyzed the mechanism of drainage noise by attempting to understand the behavior of water through experiments. In addition, the project conducted predictive calculations based on one-dimensional models in order to study means of preventing drainage noise, and the details will be discussed in this paper.

2. Mechanism of Drainage Noise

2.1. Phenomenon of Drainage Noise

Drainage noise does not occur constantly, but is a phenomenon that occurs under specific conditions. First, the behavior of water was rendered visible to help enable the characteristics of drainage noise to be understood.

2.1.1. Characteristics of drainage noise

The greater the amount of water that accumulates in the silencer, the greater its weight becomes, and this situation is undesirable from the perspectives of the occurrence of rust and the maintenance of the strength of the exhaust system components. Because of this, silencer layouts that actively encourage drainage are employed in order to reduce the amount of water accumulating. However,

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when the vehicle is idling, exhaust pressure declines and water tends to accumulate in the silencer. The frequency of drainage noise from the exhaust pipe exit is particularly high when the vehicle has been idling for long periods and water has continued to accumulate in the silencer. Figure 1 shows the process leading to the occurrence of drainage noise. As diagramed in Figs. 1(A) and (B), when water that has continued to accumulate infiltrates the outlet pipe, drainage noise will tend not to occur if the water is drained immediately from the tailpipe exit. However, if the water does not drain from the tailpipe exit, the possibility that drainage noise will occur increases. Drainage noise is an intermittent croaking sound that affects the commercial appeal of the vehicle. Figure 2 shows the results of frequency analyses conducted when drainage noise occurred and when the noise did not occur. The results show that drainage noise represents an excitation of the frequency components from low frequencies up to 1.5 kHz.

2.1.2. Behavior of water when drainage noise occurs

In order to study the behavior of water when drainage noise occurs under the conditions shown in Fig. 1(A), a transparent acrylic plate was fitted in a silencer in which drainage noise had occurred, to help enable visualization (Fig. 3).

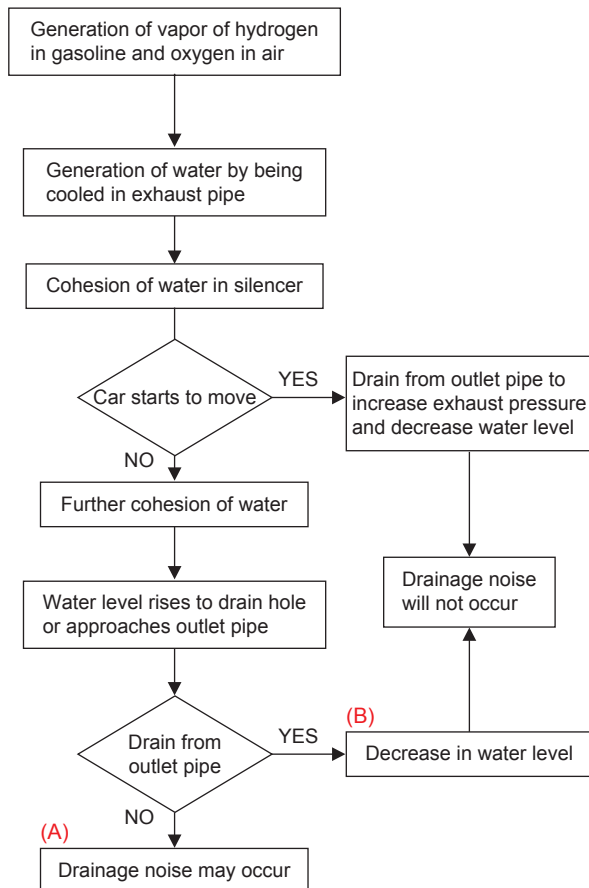


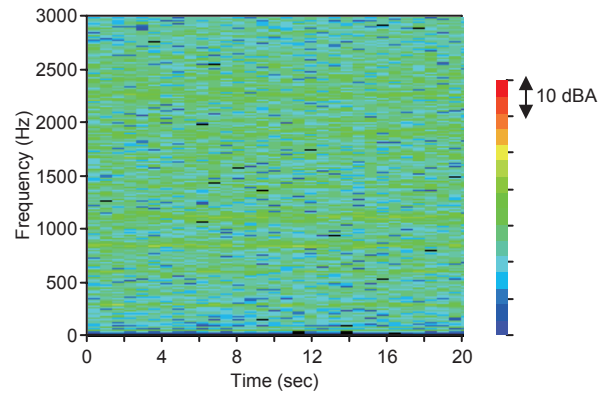
Fig. 1 Occurrence conditions of drainage noise

The results are shown in Fig. 4. When drainage noise occurs, water films are generated by fountains occurring close to the inlet of the outlet pipe, and these water films repeatedly break up and flow downstream. The results also showed that the noise occurs when these water films break up.

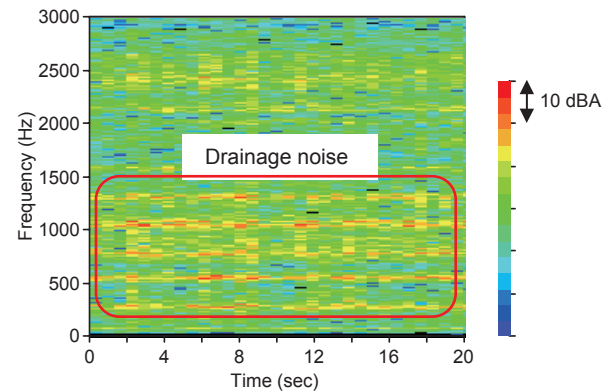
2.2. Analysis of Behavior of Water producing Drainage Noise

2.2.1. Specification of input factors

The input when drainage noise occurs is exhaust pressure, but exhaust pressure is composed of a fluctuating and a



(a) Drainage noise not occurred



(b) Drainage noise occurred

Fig. 2 Exhaust sound when drainage noise not occurred and occurred

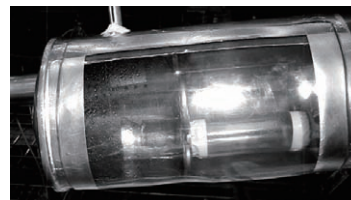
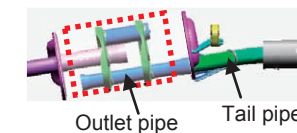


Fig. 3 Visualized silencer model

steady-state component. In order to determine which of these components was the main factor in the occurrence of drainage noise, input from a blower was used as the steady-state component and pressure fluctuations from a speaker were used as the fluctuating component (Fig. 5), and the behavior of the water and the occurrence or non-occurrence of drainage noise were studied.

As Fig. 6 shows, during the steady-state component input waves were generated but no drainage noise occurred, while when the fluctuating component was input a fountain occurred close to the outlet pipe inlet at 22 Hz, blocking the pipe and producing drainage noise.

2.2.2. Water behavior inside straight pipe model

The fact that drainage noise occurred during fluctuating component input at a specific frequency (22 Hz) in a test in which the pressure components were separated indicated that the occurrence of drainage noise was frequency-

dependent. An apparatus for testing resonance in a gas column contained in a tube, known as a Kundt's tube, has existed for more than a century. Tatsuno⁽³⁾ demonstrated in tests that fountains occur in the tubes in areas where the sound pressure is low. This means that the water that enters the tube is formed into fountains in areas where the particle velocity is high. In order to confirm these findings, using an acoustic particle velocity probe in the $\phi 41 \times 5000$ mm transparent acrylic pipe shown in Fig. 7, the present project measured sound pressure and particle velocity in the tube at the first-order resonance, 33 Hz, and the second-order resonance, 66 Hz, when a speaker was used to provide

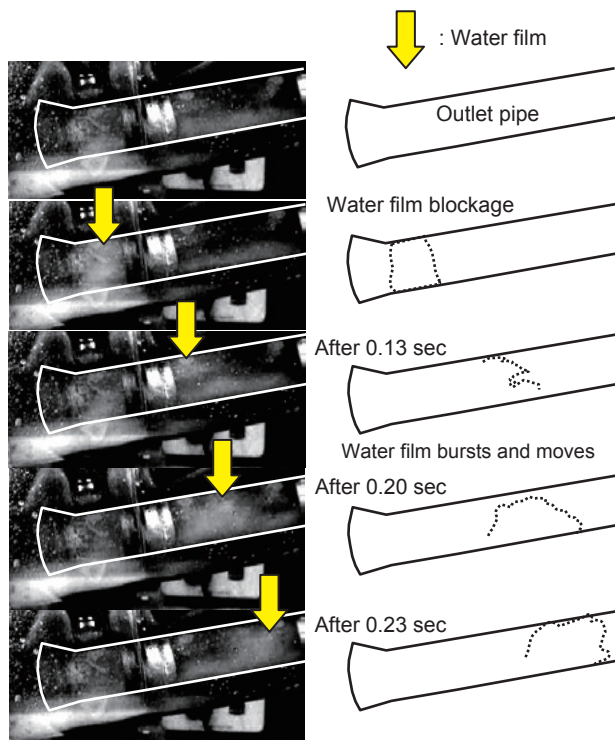


Fig. 4 Visualization of water behavior when drainage noise occurred

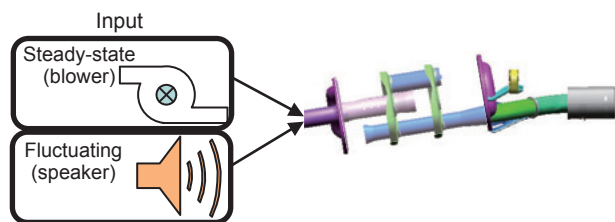
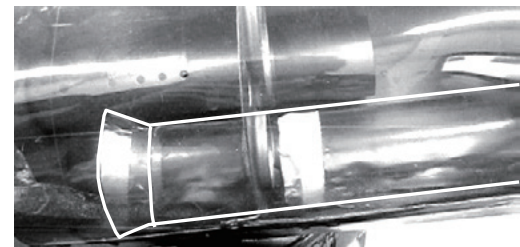
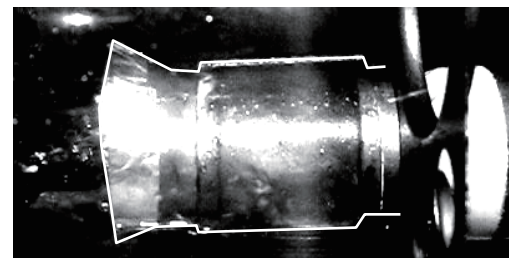


Fig. 5 Separation of influence of input components on drainage noise



(a) Steady-state input component



(b) Fluctuating input component

Fig. 6 Results of separation of input components

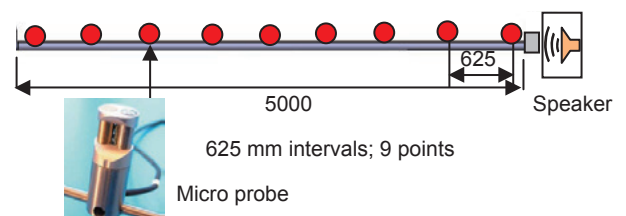


Fig. 7 Simple straight pipe model

input. In addition, water was introduced to the tube, and its behavior was observed at 28 Hz and 56 Hz. The resonance frequencies here were lower than during measurements of particle velocity because tubes with upward bends had been attached to the ends of the tube to help ensure that the water did not leak.

Figure 8 shows the results of measurements of sound pressure and particle velocity in the tube, and Fig. 9 shows results for the behavior of the water. At 28 Hz, fountains would form at both ends of the tube, where the particle velocity was high; the fountains would begin to migrate while undulating in the axial direction of the tube and would be extinguished. This process was repeated. At 56 Hz also, fountains would form close to the center of the tube where the particle velocity was high and undulate in the axial direction of the tube.

These test results indicate that water is raised into fountains in areas of the tube in which the particle velocity is high, and this results in a blockage of the tube.

2.2.3. Verification in actual system model

Tests showed that water fountains were generated and blockages occurred in areas of a straight pipe model where the particle velocity was high. In order to test

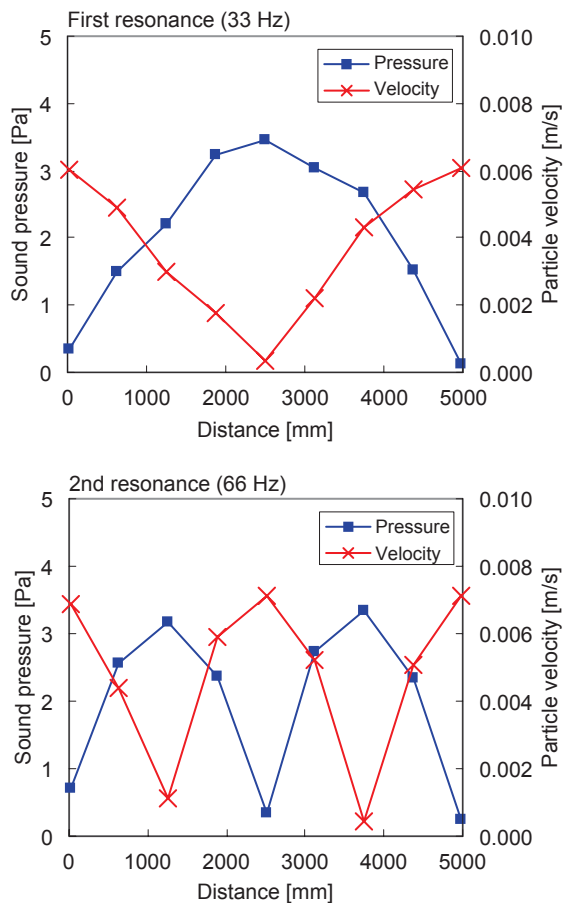


Fig. 8 Measurements of pressure and particle velocity in straight pipe

whether water would cause blockages in areas in which the particle velocity was high in a silencer with a complex configuration, an actual silencer was excited using a speaker. Figure 10 shows the points for measurement of particle velocity. Points A, B, and C were inside the outlet pipe, and points D and E were inside the silencer.

Figure 11 shows the results of measurements of the particle velocity at the silencer resonance frequency of 30 Hz, at an input of 90 dB. The results show that in an actual silencer, the area in which the blockage occurs (Point A

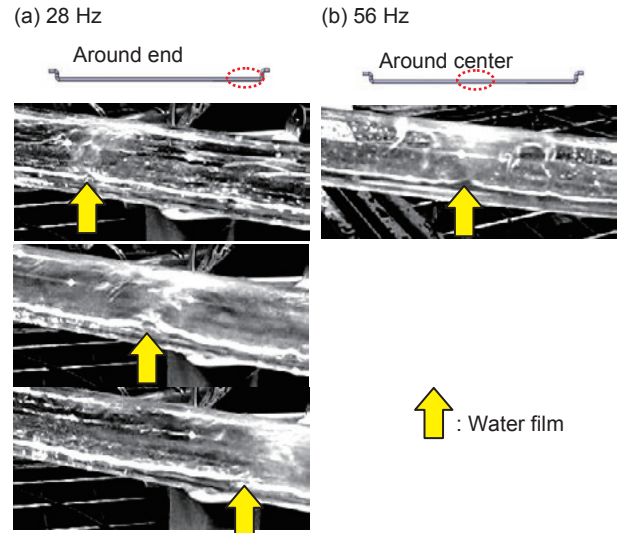


Fig. 9 Water behavior in straight pipe

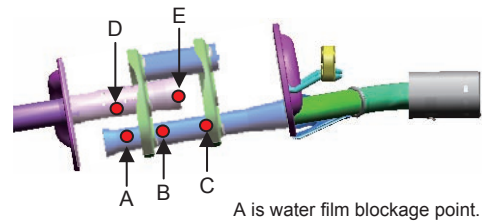


Fig. 10 Measurement points in silencer

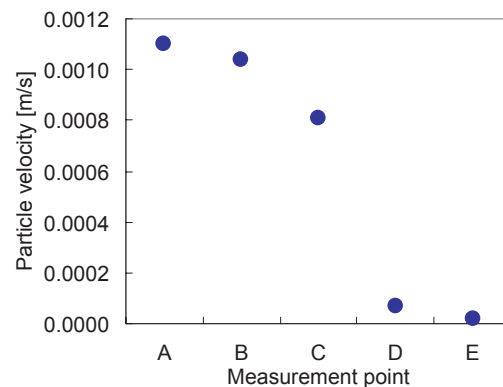


Fig. 11 Measurements results for particle velocity in silencer

in Fig. 10) coincides with the area in which the particle velocity is at its maximum. In conditions in which drainage noise occurs in an actual silencer, water forms fountains in areas in which the particle velocity is highest, and the pipe becomes blocked. These results indicate the following mechanism for the generation of drainage noise.

If water exists in the area in which the particle velocity is at its maximum at the resonance frequency of the silencer, fountains will be formed, and noise will be generated following the blockage of the pipe by those water films.

3. Study of Prevention of Drainage Noise

Based on the mechanism of drainage noise discussed in Chapter 2, the following three measures for prevention of the noise could be considered:

- (1) Modification of the resonance frequencies of the silencer to prevent them falling within the idling range of the engine
- (2) Reduction of the particle velocity
- (3) Reduction of the amount of water accumulating in the silencer (Drainage noise does not occur in the absence of water)

Modification of the low-frequency resonance frequency, as suggested in (1), would necessitate extensive modification of the length of the exhaust system and of the volume of the silencer, and would therefore be challenging in practice. The concrete method of realizing (2), positioning holes close to the areas of the outlet pipe inside the silencer where the particle velocity is highest in order to reduce the velocity, is already in use. If the amount of water accumulating in the silencer could be reduced, as indicated in (3), it would present advantages from the perspectives of rust prevention and maintenance of strength in addition to preventing drainage noise. Given this, this chapter will discuss evidence obtained from tests concerning the mechanism of drainage of water that accumulated in the silencer from the tailpipe, as shown in Fig. 1(B), and a method for its prediction.

3.1. Prediction of Drainage Performance

In order to study factors affecting drainage performance, the behavior of water was visualized using the test model shown in Fig. 12, and pressure measurements were conducted in the area indicated in the diagram. An inline 4-cylinder engine was employed, operated in the idling range. The test results showed that when there is extensive migration of the water films and they are drained, the positive pressure peak of the outlet pipe pressure differential (ΔP : $P_1 - P_2$) instantaneously increases (the circled area in Fig. 13). A bypass pipe was positioned on the upstream side of the silencer; the pressure differential ΔP in the silencer outlet pipe was varied by varying the diameter of this pipe, and the amount of water accumulating in the silencer was measured. Figure 14 shows the average values of the positive pressure peaks of the pressure differential ΔP

and the amount of accumulated water in the silencer. These results show that the amount of accumulated water in the silencer declines in proportion with the increase in the peak value of ΔP .

Based on this, it is conjectured that the water films migrate downstream and are discharged from the tailpipe because the pressure differential ΔP increases with the addition of an instantaneous irregular component to the fluctuating component of pulsative pressure in the outlet pipe.

Given that drainage noise would not occur if the amount of water accumulating in the silencer were reduced, a physical model for the prediction of the amount of water accumulating in the silencer when the vehicle was idling was formularized and studied in tests in order to study orientations for measures to increase drainage performance.

3.1.1. Construction and formularization of drainage model

The behavior of the gas-liquid interface in a gas-liquid two-phase flow in which gases and liquids are mixed involves rather complex phenomena, and accurate prediction based on theoretical analyses represents a challenge. Recently, reports have appeared concerning the elucidation of the phenomena employing the MAC, VOF,

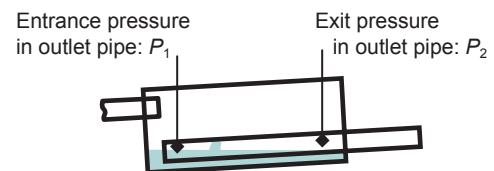


Fig. 12 Test model for study of drainage noise and drain performance

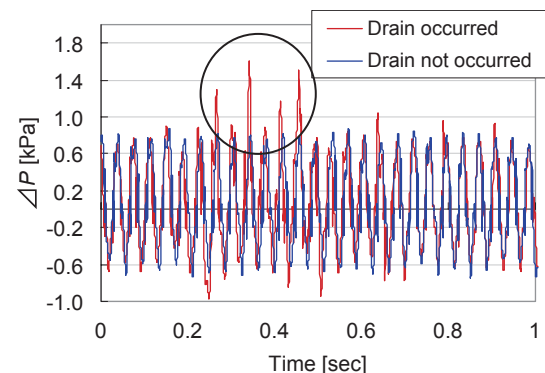


Fig. 13 Difference in pressure in outlet pipe

CIP, and other methods of Navier-Stokes numerical analysis and visualization experiments using high-speed cameras⁽²⁾.

In order to predict drainage noise, it is necessary to calculate the behavior of the gas-liquid interface, but it was possible to employ a simpler model if the phenomenon was restricted to the degree of migration of the water films. Focusing on the fact that ΔP necessarily increased when the water films migrated, based on the test results discussed above, the authors conjectured that the phenomenon could be explained using two models (of the water films that blocked the interior of the pipe and of the flow of exhaust gas), and attempted to formularize these.

First, as a model of the drainage of water, a dynamics model will be considered in which the water films that block the pipe are pushed from the pipe by the pressure differential ΔP before and after the blockage occurs. As shown in Fig. 15, the internal diameter and mass of the water film are termed d and m , respectively; the velocity of migration of the film when acted upon by force F is termed V_f , the distance it migrates within the pipe is termed L , and its height at that time is termed H . The force acting on the film, F , is equivalent to the pressure differential ΔP before and after the formation of the film multiplied by the surface area of the pipe, S .

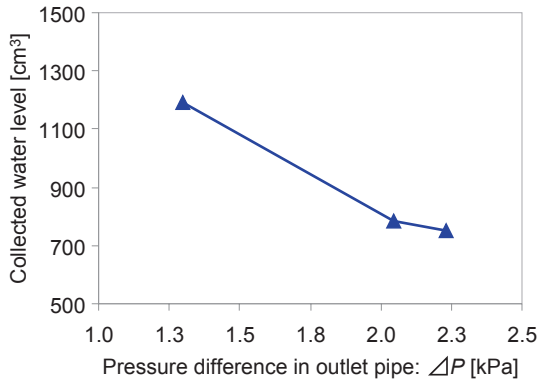


Fig. 14 Relation between ΔP and collected water level

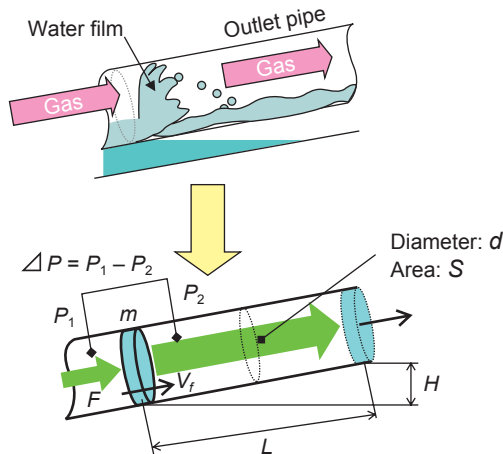


Fig. 15 Model of water film

Based on motion equations, the velocity of migration of the water film, V_f , is

$$\begin{aligned} m \cdot \frac{dV_f}{dt} &= F \\ &= (P_1 - P_2) \cdot S \\ V_f &= \frac{1}{m} \cdot \Delta P \cdot S \cdot \Delta t \end{aligned} \quad (1)$$

ΔP is the pressure differential before and after the formation of the film. If gravitational acceleration is termed g , friction loss in the pipe ΔH , and the drag coefficient of the pipe λ , then based on the principle of conservation of energy, the velocity determined in Eq. (1) gives

$$\begin{aligned} \frac{1}{2} \cdot m \cdot V_f^2 &= m \cdot g \cdot H + m \cdot g \cdot \Delta H \\ H &= \left(\frac{1}{2g} \right) \cdot V_f^2 - \Delta H \\ &= \left(\frac{1}{2g} \right) \cdot V_f^2 - \lambda \cdot \frac{L}{d} \cdot \frac{V_f^2}{2g} \end{aligned} \quad (2)$$

and the height, H , which the water film blocking the outlet pipe is able to reach can be determined. Here, the equation below, known as the Darcy-Weisbach equation, is used for ΔH . The equation indicates that friction loss has a great effect on flow velocity.

$$\Delta H = \lambda \cdot \frac{L}{d} \cdot \frac{V_f^2}{2g} \quad (3)$$

Next, the fluid model shown in Fig. 16, in which minute pressure waves are propagated in a static fluid, was employed for the gas flow.

Looking at the propagation of pressure waves in the

Propagation of micro-change, considering compression

Situation with wave surface moving at sound speed "a"

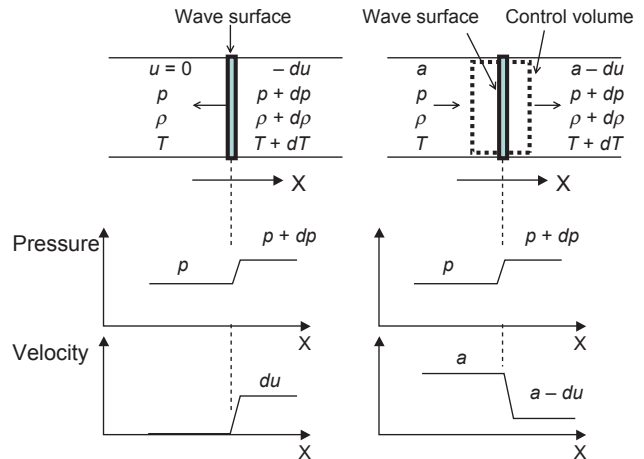


Fig. 16 Model of gas flow

negative direction of the X axis in the static fluid, pressure changes by dP and density changes by $d\rho$ due to the passage of the wave surface. It is challenging to observe and analyze a moving compression wave from outside the system. If an observer riding the compression wave and moving at speed a is therefore imagined, the speed of the flow passing the wave surface is reduced from a to $a-du$, while the pressure increases from P to $P+dP$ and the density increases from ρ to $\rho+d\rho$. Because the principle of conservation of motion is applied here, if the control volume surrounding the wave surface is considered and the force acting on the control volume is made the left-hand term and the degree of motion is made the right-hand term, then the degree of change in pressure is given by

$$\begin{aligned} S \cdot [P - (P + dP)] &= \rho \cdot a \cdot S \cdot [(a - du) - a] \\ dP &= \rho \cdot a \cdot du \end{aligned} \quad (4)$$

If it is hypothesized here that the outlet pipe is blocked by the water film and the gas flowing at velocity u is instantaneously blocked and becomes static, the change in velocity, du , is given by

$$\begin{aligned} du &= u - 0 \\ &= u \end{aligned} \quad (5)$$

From Eqs. (4) and (5), the pressure differential before and after the blockage of the pipe by the water film, ΔP , is determined by the following equation:

$$\Delta P = \rho \cdot a \cdot u \quad (6)$$

This is known to be a pressure increase due to the water hammer phenomenon⁽⁴⁾.

In addition, the gas velocity, u , is found using the following equation:

$$u = \frac{Q}{S} \quad (7)$$

Q is volumetric flow, and is determined mainly using the engine displacement.

3.1.2. Validation of drainage model

The pressure differential before and after the blockage of the interior of the outlet pipe by the water film, ΔP , and the gas flow velocity are found using Eqs. (6) and (7), respectively. Figure 17 shows a comparison of calculated and test figures. A pitot tube was employed for the measurement of the gas flow velocity. Using the pressure differential, ΔP , the height to which the water film is able to rise in the outlet pipe can be found from Eqs. (1) and (2). Figure 18 shows a comparison of calculation and test results. The tests employed the model shown in Fig. 12, using outlet pipes of three different diameters, and varying

the silencer angle in 6° increments. In addition, the heights reached by the water films were determined from test images. The calculation conditions were density $\rho=1.164 \text{ kg/m}^3$, sound speed $a=348.9 \text{ m/s}$, water film mass $m=0.005 \text{ kg}$ (mass as measured in tests), friction coefficient $\lambda=0.027$, $\Delta t=0.038 \text{ s}$ (at an idling speed of 800 rpm, the 2nd-order harmonic of the explosion is 26.6 Hz; Δt at one explosion). Because the internal walls of the pipe were smooth and the Reynolds number was less than 10^5 , the Blasius equation⁽⁵⁾ was used to find the friction coefficient.

3.2. Discussion

The two test plots for the gas velocity and the pressure differential ΔP as shown in Fig. 17 correspond well with calculated figures.

Figure 18 indicates that the pressure differential ΔP increases in proportion to the reduction in the diameter of the outlet pipe, and the height reached by the water film, H , also increases in proportion to this parameter. It is considered that differences occurring in ΔP at the same pipe diameter can be explained by the fact that variations occur in the thickness of the water films because the formation of the films is based on unstable gas-liquid interface phenomena. However, test results for the relationship between ΔP and H display a good correlation with calculation results.

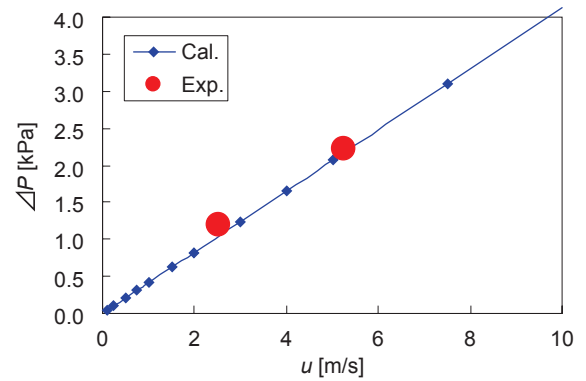


Fig. 17 Relation between u (gas velocity) and ΔP (pressure difference in outlet pipe)

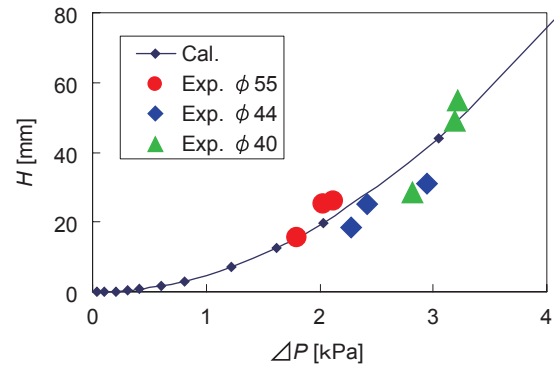


Fig. 18 Relation between ΔP (Pressure difference) and H (height reached by water film)

The results of the calculations based on the simple models formulated in the previous chapter demonstrated that the height of the water film, in other words drainage ability, could be reproduced with serviceable accuracy.

Because the gas velocity is determined by the engine displacement and the outlet pipe diameter, as a means of increasing drainage performance, an appropriate figure for the pipe diameter should first be decided on based on considerations of exhaust outlet noise and pressure loss due to exhaust gas flow. Following this, it would be effective to set the height between the inlet and outlet of the outlet pipe lower than the height that can be reached by the water film, taking into consideration the amount of water that will accumulate in the silencer.

4. Conclusion

The interior of a silencer was visualized, measurements of pressure in exhaust pipes were taken, and predictive calculations were conducted using a one-dimensional model in order to elucidate the mechanism of occurrence of drainage noise and to predict its occurrence. The following results were obtained:

- (1) Pulsative pressure during engine operation and exhaust resonance is a factor in drainage noise, and it mainly occurs in the idling range.
- (2) Blockage of the exhaust pipe by water occurs in areas in which the particle velocity is highest.
- (3) The water films that block the exhaust pipe repeatedly flow downstream while breaking up, and drainage noise occurs when the film breaks up.
- (4) The movement of the water film downstream is promoted and drainage performance increases in proportion to the magnitude of the pressure differential before and after the occurrence of the blockage due to the water film, ΔP . Increasing ΔP was shown to be an effective measure against drainage noise.

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