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A Jet-Tone Orifice Number for Orifices of Small Thickness-Diameter Ratio

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The dependence of a jet-tone orifice number $tf/(\Delta p/\rho)^{\frac{1}{2}}$ on Reynolds number $[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ is shown for thin sharp-edged circular orifices whose thickness and diameter both vary from approximately $\frac{1}{8}$ to $\frac{3}{8}$ in, where t is thickness of orifice plate; f, frequency; Δp, pressure difference across orifice; ρ density; and μ, viscosity of gas. Each jet-tone, in general, is composed of harmonics (fundamental and over-tones) as well as subharmonics (tones whose frequencies are less than the fundamental). The subharmonics are relatively unsteady in amplitude compared to the harmonics and may at times have a greater amplitude. The jet-tones at low Reynolds numbers appear relatively free of noise background. In general, as Reynolds number is increased to high values the noise background at first engulfs the subharmonics, then the harmonics. The fundamental is the last to remain, finally disappearing in the noise background.

INTRODUCTION

As Reynolds number of a fluid flowing through a sharp-edged circular orifice is increased from zero, a distinct tone suddenly appears at a definite Reynolds number. With increase of Reynolds number, the apparent acoustic frequency of this tone continues to increase. Eventually, however, the tone merges into the white noise background emitted by the jet. The tone is created by periodic shedding of vortices from the orifice, which give rise to a sound field in the surrounding medium. In general, the tone in the sound field is composed of a number of eigenfrequencies aerodynamically self-excited by the flow.

Hydrodynamic studies of the flow pattern in sharp-edged pipe entrances using colored liquid filament tracer techniques lead to some insight into the mechanism of generation of these tones.[1–7] At a Reynolds number (Re) below, 300, a colored liquid filament injected into the stream, upstream and near the edge of the pipe entrance, initially curves inward toward the pipe axis and then settles down to a uniform flow along the tube walls (undisturbed laminar flow). Above approximately Re 300 disturbances originate at the edge of the pipe entrance to produce a waviness of the colored filament, which is especially pronounced in the transition layer (outer part of the boundary layer) separating the main flow from the main part of the boundary layer. With further increase of flow velocity the waves acquire greater amplitude. If the colored filament is injected into the stream farther towards the central axis of the pipe, the beginning of the waves is displaced more downstream from the pipe entrance. With further increase of velocity, the disturbance becomes so great that the transition layer rolls itself up periodically into small, discrete, closed, ring-like whirls, or vortices, which wander downstream in analogy to the Bénard-Kármán vortex street. Traces of these vortices appear in the boundary layer slightly downstream from the pipe entrance at Re approximately 1120. Farther downstream they acquire an approximately constant axial distance of separation in the boundary layer. The greater the Re, the farther the vortices extend into the pipe before becoming completely attenuated. Up to approximately Re 1600, the disturbances eventually attenuate downstream and the fluid returns to a laminar flow.

At Re 1600 to 1700, the transition layer suddenly rolls itself into a large, ringlike vortex whose diameter henceforth determines the contraction of the effective entrance-flow cross section of the pipe. Smaller vortices are periodically cast off from this large vortex. Always associated with this change of flow at the pipe entrance is a transition from laminar to turbulent flow throughout the pipe. That is, the disturbances no longer attenuate. The foregoing vortex formations near the entrance of a pipe might be considered indicative of those in an orifice of appreciable thickness.

Early studies summarized elsewhere[8–12] are in disagreement as to whether the geometrical magnitude determining the frequency of a jet tone is the orifice-plate diameter or the orifice-plate thickness. Recent studies of jet-like tones from sharp-edged circular orifices[13] using air indicate that eigenton frequency is proportional to jet-flow velocity and inversely proportional to orifice thickness, that the appropriate characteristic length in the associated Reynolds number is the thickness of the orifice plate, and that the sound is created by circular vortex rings shed periodically from the orifice. These studies may not, it appears, have been carried out, on entirely pure jet-tones since the tones reported were in general not complex and since a resonating pipe preceded the orifice[14] causing the frequency of the sound partly to follow the resonance curve of the pipe and the intensity of the sound therefore to fluctuate with increase in flow velocity. A more recent study[15] carried out on pure jet-tones over a somewhat larger range of pertinent variables also indicates that orifice-plate thickness is an important geometrical variable determining frequency and that frequency and sound amplitude vary with change of flow velocity.

Related studies have been made of the frequency of vibration associated with discharge of liquids through circular orifices *into free air*. Frequency of vibration of the sound was found pro-

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[4] See reference 3, Vol. IV, part 4, pp. 130–138.
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portional to the square root of the differential pressure across the orifice (that is, to the velocity of flow) and inversely proportional to the diameter of the orifice.[16] In a later article[17] the frequency was reported inversely proportional to the orifice-plate thickness. Tones were observed only when the ratio of thickness to diameter of the orifice lay between 0.5 and 2. The thicker the orifice plate, the lower is the differential pressure required to produce a given frequency. Greatest sound intensity was observed when orifice diameter equaled orifice-plate thickness. The foregoing is an acoustic phenomenon analogous to that presented by the same orifice when air is discharged instead of a liquid.

On the other hand, when liquid is discharged through the orifice into a *large body of the same liquid*, sound is produced over a much greater range of orifice thickness-diameter ratio (0.1 to 2) than the foregoing. Only when the orifice becomes almost a knife-edge does the sound disappear. Otherwise this phenomenon is much the same as when the liquid discharges[16] into air.

Studies have been made of the effect of sharpness of orifice edges on the character of jet tones.[18] It is especially important that the entrance edge of the orifice be sharp for maximum efficiency in the production of tones. This is not as true for the exit. Wide variation in geometry of this may be tolerated.

Most vortex formations reported in the literature created by fluid flow through orifices or around obstacles have been simple, periodic, relatively uniform in size, and of the same order of magnitude as the obstacle, i.e., like the Bénard-Kármán vortex street. Another type of vortex system, however, has also been reported. This may coexist with the Bénard-Kármán vortex street under a certain range of conditions. In general, it has a higher frequency and is smaller, and the individual vortices are strung together like links of a chain. These vortices have been referred to as secondary vortices or *tourbillions adjoints*.[19–22] If the flow is about an obstacle, they appear in the form of a double chain along the wake of the obstacle. Under certain conditions the frequency of the two types of vortices may be made to approach each other; under other conditions, the larger Bénard-Kármán vortices will quickly absorb or sweep out the secondaries.[19,21,23]

Many studies have been made of the periodic segmentation and change in geometrical form of a jet of liquid while issuing from an orifice into the atmosphere.[24] Eventually, under proper conditions, the jet breaks up into a periodic succession of similar droplets. In one case the droplets arise as a result of random disturbances of the equilibrium flow pattern and an interplay of surface tension, inertia, and, to some extent, the viscosity of the liquid. In another the frictional resistance of the air on the jet becomes more important than surface tension.[25,26]

The present paper is concerned with determination of the relation between acoustic eigenfrequencies self-excited in an air jet while traversing sharp-edged circular orifices possessing a relatively small thickness-diameter ratio. A transition sets in for higher ratios, leading to a totally different regime of jet-tone frequencies, which will be reported at a future date.

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APPARATUS

These studies were carried out with air and the experimental equipment described elsewhere[10,11] except for the following:

1. The stilling tank, approximately 9.5 in diameter and 23 in long to which the orifices were attached, was lined with loose cloth and felt to eliminate cavity resonances.

2. The orifice plates were of steel. The two parallel surfaces were carefully ground parallel. All orifice holes up to and including $\frac{1}{4}$ in diameter were made by first drilling a hole to within a few thousandths of an inch of the required size and then honing with a flexible drive. All holes above $\frac{1}{4}$ in diameter were finished with an internal grinding wheel. Holes were not burred. Orifices were carefully cleaned before each run.

3. To stabilize the flow before it entered the orifice, in several of the studies, a stainless steel screen was placed $\frac{1}{2}$ in in front of the orifice. All air passed through this screen before entering the orifice. The mesh was a screen composed of two sets of wires (100 per inch, each 0.0015 in diameter) woven together at right angles to each other. For studies reported in this paper, the screen appeared to produce no outstanding effect.

4. The jet-tones were picked up by a sensitive high frequency response crystal pickup placed in the vicinity of the edge of the orifice far enough away to avoid influencing the jet.

EXPERIMENTAL RESULTS

Justification of the method of presentation of the experimental data is based on the following considerations: *Pfeifentöne* are excited and maintained by the same aerodynamic mechanism of periodic vortex shedding as jet-tones.[27] Presumably, also, under the the same aerodynamic conditions of flow the primary *Pfeifenton* frequency of a pipe-orifice combination has approximately the same numerical value as the jet-tone frequency of the orifice alone (i.e., separated from the resonating effects of the attached pipe). It is therefore expected that the form of the dependence of the primary *Pfeifenton* orifice constant on Re, found elsewhere,[14] might serve here equally well for presenting the dependence of jet-tone frequency on Re. For primary *Pfeifentöne*, it was shown that the nondimensional number $ft/(\Delta p/\rho)^{\frac{1}{2}}$ relating the dependence of differential pressure Δp across the orifice to the density ρ of the gas, thickness of t of the orifice plate terminating the pipe, and the frequency f of the primary *Pfeifentöne* is the proper orifice number to be used over the range of variation of the parameters, pipelength, orifice diameter, differential pressure across orifice, and *Pfeifenton* frequency studied. It was also shown that this orifice number is a function of a Re of the form $[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ where μ is the viscosity of the

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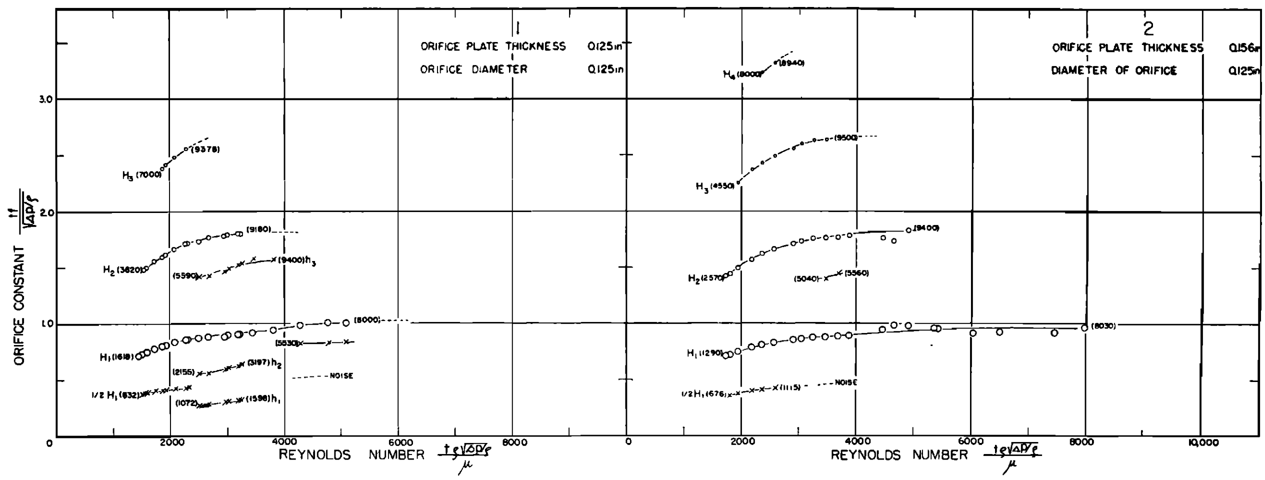
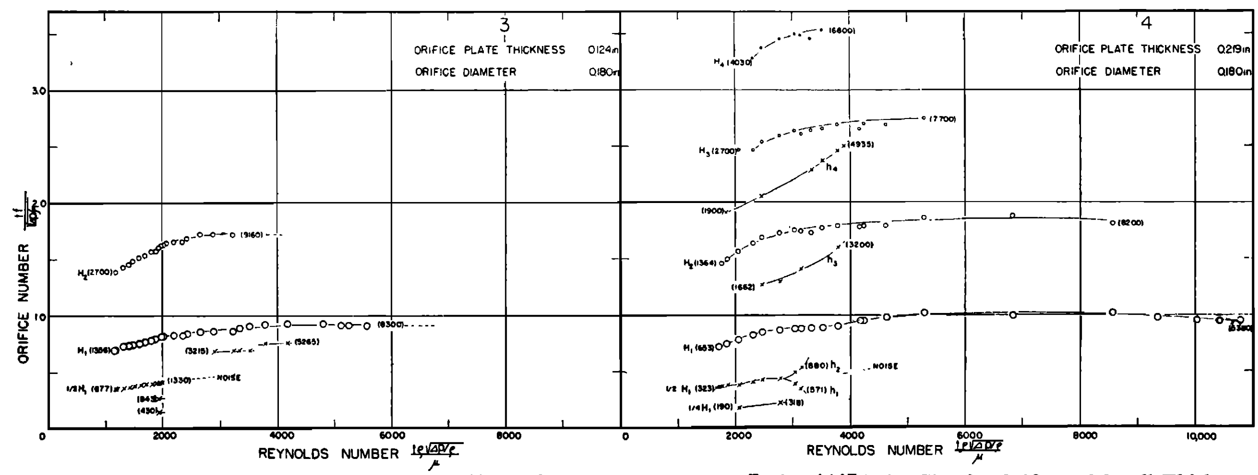


FIGS. 1 AND 2. Dependence of Orifice Number $tf/(\Delta p/\rho)^{\frac{1}{2}}$ on Reynolds number $[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ for Circular Orifices of Small Thickness-Diameter Ratio. Orifice diameter is 0.125 in; orifice-plate thickness, 0.125 and 0.156 in. Symbol t represents orifice-plate thickness; f, eigenton frequency; Δp, differential pressure across orifice plate; ρ, density of gas; and μ, viscosity of gas.



FIGS. 3 AND 4. Dependence of Orifice Number $tf/(\Delta p/\rho)^{\frac{1}{2}}$ on Reynolds number $[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ for Circular Orifices of Small Thickness-Diameter Ratio. Orifice diameter is 0.180 in; orifice-plate thickness, 0.124 and 0.219 in. Symbol t represents orfice-plate thickness; f, eigenton frequency; Δp, differential pressure across orifice plate; ρ, density of gas; and μ, viscosity of gas.

gas. Accordingly, the data in the present study have been correlated according to this orifice number and Re.

Figures 1 to 8 present the experimental results for jet-tones produced by orifices whose diameters vary from 0.125 to 0.375 and thickness from 0.124 to 0.375 in. The eigenfrequencies in each figure for each orifice are shown for as wide a range of Re as detectable. As the Re of flow slowly increases from zero, the jet-tone eigenfrequencies suddenly appear at the values indicated. When Re reaches higher values, the amplitude of the eigenfrequencies decrease, finally merging into the acoustic noise background into which all eigenfrequencies become transformed.

A comparison of the figures shows the common presence of the harmonics H_1, H_2, etc. The order of decrease in amplitude of these harmonics is H_1, H_2, etc., as indicated in the figures by the progressive decrease in size of the hollow circles. The highest harmonic is always very faint. The numerical value of the orifice numbers rise markedly at first with Re to become asymptotically relatively constant at higher Re.

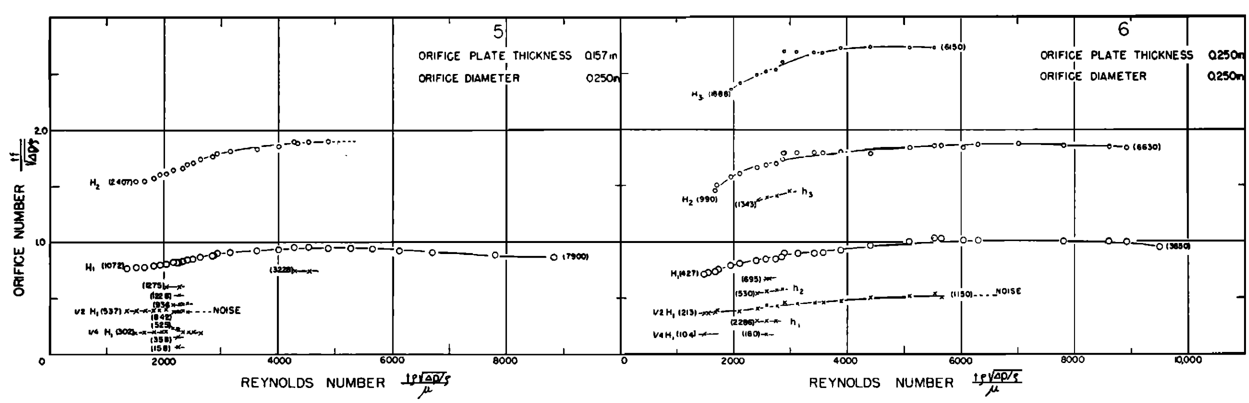
Each jet-tone, when impressed on the y-axis of an oscilloscope with a suitable x-axis sweep, appears as a distorted sine wave. The amplitude of the waves, as well as their dc level, is not constant in time. In general, both vary at some simple subharmonic frequency of H_1, i.e., $\frac{1}{2}H_1$, $\frac{1}{3}H_1$, etc. Comparison of the subharmonics $\frac{1}{2}H_1$, $\frac{1}{3}H_1$, etc., with the harmonics H_1, H_2, etc., shows the amplitude of the former to be much more unsteady and fluctuating with time.

Jet-tones at low Re appear relatively free of noise background. With increase of Re, noise appears first as background to the subharmonics of H_1, frequently around the frequency $\frac{1}{2}H_1$, tending to make the peak of $\frac{1}{2}H_1$ broad. This broadening is not symmetrical. For a given jet-tone, the amplitude of the noise as a function of frequency has the appearance of a plateau on the upper frequency end of which is located the subharmonic. With increase of frequency above the peak of the subharmonic, therefore, the intensity of the noise decreases relatively rapidly towards zero; with decrease of frequency below that of the peak, the intensity remains relatively constant for a considerable frequency range. As Re of the jet-tone is raised still further, noise engulfs the subharmonics and soon begins to encroach on the harmonics until all of the harmonics except H_1 become washed out. Eventually, even H_1 loses its identity and merges into the background of noise. Although the intensity of the noise itself in general always appears to increase continuously with increase of Re, the intensity of the eigenfrequencies does not. The intensity of the latter first appears to rise to a maximum and then fall to zero.

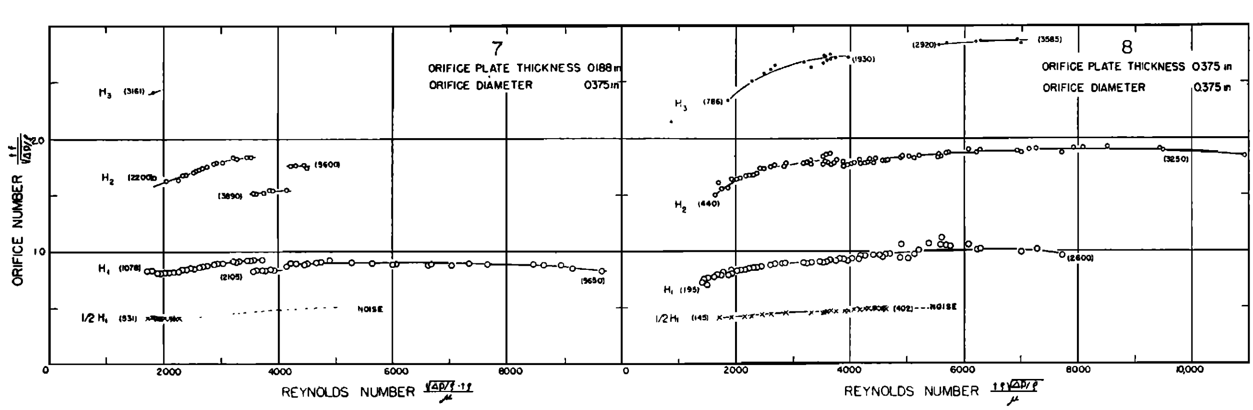
H_1 persists in general over a greater range of Re than any of the others. As Re is gradually increased from zero by increasing the flow velocity, H_1 is the first to appear suddenly, or is among the first to appear. It is also, in general, the last to become obliterated in the increasing intensity of noise background with increase of Re.

H_1 also has the largest amplitude of those harmonics in the jet-tone whose amplitudes remain relatively constant and stable with time. It is, however, not always the harmonic in the jet-tone with the largest amplitude. Frequently subharmonics, such as $\frac{1}{2}H_1$, over part of the Re range in Figs. 3 and 4, $\frac{1}{4}H_1$ and $\frac{1}{2}H_1$ in Fig. 5, and h_1 and the component below this in Fig. 6 have a larger amplitude than H_1. The amplitude of these harmonics are in general very unsteady, sometimes fluctuating over an amplitude range of 80 percent of the maximum amplitude in a time interval of the order of a second.

Harmonics are present whose frequencies are not relatively simple multiples or submultiples of H_1. These are indicated, for example, in Fig. 1 by h_1, h_2, and h_3; in Fig. 4 by $h_1 \cdots h_4$; and in Fig. 6 by h_1, h_2, and h_3. Very simple sum and difference relations are found between the frequencies of these (expressed in terms of orifice numbers) and the other harmonics. In Fig. 1 it appears that $h_1 = h_2 - h_1 = H_1 - h_2 = 2H_1 - h_3$, $h_2 = H_1 - h_1 = h_3 - H_1$, and also $h_3 = h_2 + H_1$; in Fig. 4, $h_1 = H_1 - h_2 = 2H_1 - h_3 = 3H_1 - h_4$, $h_2 = H_1 - h_1 = h_3 - H_1 = h_4 - 2H_1$, and also $h_4 = h_2 + 2H_1 = h_3 + H_1$; in Fig. 6, $h_1 = H_1 - h_2 = 2H_1 - h_3$, $h_2 = H_1 - h_1 = h_3 - H_1$, and also $h_3 = h_2 + H_1$. Frequently, therefore, when anomolous harmonics above H_1 appear, subharmonics also appear entailing sum and difference relations between their office numbers. Often a jet-tone may be composed



FIGS. 5 AND 6. Dependence of Orifice Number $tf/(\Delta p/\rho)^{\frac{1}{2}}$ on Reynolds number $[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ for Circular Orifices of Small Thickness-Diameter Ratio. Orifice diameter is 0.250 in; orifice-plate thickness, 0.157 and 0.250 in. Symbol t represents orifice-plate thickness; f, eigenton frequency; Δp, differential pressure across orifice plates ρ, density of gas; and μ, viscosity of gas.



FIGS. 7 AND 8. Dependence of Orifice Number $tf/(\Delta p/\rho)^{\frac{1}{2}}$ on Reynolds number $[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ for Circular Orifices of Small Thickness-Diameter Ratio. Orifice diameter is 0.375 in; orifice-plate thickness, 0.188 and 0.375 in. Symbol t represents orifice-plate thickness; f, eigenton frequency; Δp, differential pressure across orifice plate; ρ, density of gas; and μ, viscosity of gas.

of many subharmonics as in Figs. 5 and 6. Again, between the orifice numbers of these many subharmonics, simple sum and difference relations may be found.

With increase of gas-flow velocity in the vicinity of the top of the knee of the curves, the jet-tone changes from a smooth, even, and pleasing sound to a sputtering, rattling sound associated with an instability in the value of the frequency. In this condition a slight mecahnical disturbance of the flow can occasionally transform the jet-tone from one frequency to another. Frequently these easily initiated transition in the jet-tone occur without any appreciable change in the frequency of H_1. In other cases, as Figs. 7 and 8 for large diameter orifices, there is an abrupt change. Usually, also, in this vicinity there begins to arise an appreciable noise background for the subharmonic frequencies, with a resulting tendency to obliterate and to wash out the subharmonics. With further increase of gas-flow velocity, the jet-tone becomes harsh, dissonant, and sometimes shrill. This may be related to the observation that in this range of Re the orifice numbers H_1, H_2, etc., are not exact multiples of each other.

DISCUSSION

All of the figures show the same general dependence of orifice number $tf/(\Delta p/\rho)^{\frac{1}{2}}$ on Re $[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ for jet-tones produced by orifices having the range of variations of t/d shown (where d is orifice diameter). The same behavior extends to somewhat larger and also to somewhat smaller ratios than are indicated by the figures presented. For thick orifices, on the other hand, the characteristic length d and not t should probably be used in the two dimensionless numbers. This will be considered in a later paper.

It has been proposed that the mechanism involved in the creation of jet-tones is also the source of excitation of *Pfeifentöne*.[10,11,14,27] It might therefore be presumed that the primary *Pfeifenton* orifice number found elsewhere[11] should be included in one of the orifice numbers shown in Figs. 1 to 8 if the orifice used were the same in the two cases. The orifices were not the same. The *Pfiefentöne* studies[11] were carried out on a family of thinner orifice plates (smaller t/d) than the present jet-tone studies. Although the same nondimensional orifice number and Re are found applicable to both studies, the functional dependence of the orifice number on Re will be found not the same. A paper also to be presented later will show a different functional dependence of orifice number on Re for orifices thinner than those in this study.

The present study of jet-tones indicates that the orifice number at first increases with increase of Re and then asymptotically approaches a relatively constant value. This is the same qualitative trend found for primary *Pfeifenton* orifice numbers.[11] A similar asymptotic increase of Strouhal's number fd/V (where d is diameter of circular cylinder and V is the velocity of flow of the fluid) with increase of Re is also found.[28–31]

This condition prompts one to raise the question as to whether the asymptotic increase of orifice number with increase of Re is caused by the decreasing relative importance of the process of diffusion of vorticity per vortex, away from the nascent vortex, with increase of Re. It seems reasonable to expect that not all of the vorticity fed into the vortex by the jet stream during its formation is retained by the vortex. Some is continuously diffused away and lost during the formation of the vortex; the amount, decreasing with the time required in forming the vortex. Simple analysis of the orifice number leads one to the conclusion that its value is a measure of the total amount of vorticity required of the jet stream for the formation of a single vortex, that is, the length of column of fluid that must pass through the orifice for each vortex formed. The greater the orifice number, and, therefore, the jet-tone frequency, the smaller is the total amount of vorticity required of the flow stream to form a complete vortex because a smaller time interval is allowed for the diffusion and dissipation of vorticity away from each nascent vortex. In the limit with increase of jet-tone frequency, the amount of vorticity dissipated from the vortex during its formation should become negligible compared to the amount of vorticity possessed by the completely developed vortex. Thus the process of dissipation of vorticity during the formation of the vortex might be expected to be negligible for the horizontal compared with the intitial part of the curves.

It appears unnecessary to assume that a separate vortex is shed for each harmonic observed in a jet-tone. According to the present state of available experimental knowledge, it is reasonable to consider that several harmonics and subharmonics may arise from a single succession of vortices. The periodic shedding of vortices from the orifice gives rise to periodic acoustic impulses of frequency H_1 radiating from the jet. This succession of impulses may be built up of harmonics H_1, H_2, etc. Also, each of the vortices shed may not have exactly the same strength as the preceding or the following. If, for example, alternate vortices are strong, one might expect the appearance of the subharmonic $\frac{1}{2}H_1$ which is found in all the figures. The appearance of subharmonics in the field of acoustics is not uncommon.[32]

The curves showing the dependence of orifice number on Re are all very similar for the range of different orifices presented. It must be noted, though, that the present studies did not permit variation of the density and viscosity of the gas, two of the variables in Re.

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