Fluid mechanical aspects of open- and closed-toe flue organ pipe voicing

D. Steenbrugge[1]
[1]Hogeschool Gent, Belgium

Abstract
Open- and closed-toe voicing of flue organ pipes constitute two opposite extremes of possible ways to determine the air-jet flow rate through the flue. The latter method offers more voicing control parameters and thus more flexibility, at the expense of a necessary pressure loss at the toe hole. Another difference between both cases arises from different air-jet characteristics, such as velocity profile, Re number, flow momentum or aspect ratio, the latter influencing jet instability. Furthermore, for closed-toe voicing, the flow field in the pipe foot is modified by an axisymmetric air jet created through the highly constricted toe hole. Velocity measurements on air jets, pressure measurements in the pipe foot are presented, compared and discussed for both voicing methods. The ratio of flue to toe hole area is shown to be the sole pipe parameter to entirely determine the jet velocity and can be useful to quantitatively characterize flue and toe hole voicing. Open-toe voicing turns out to be the more delicate and low-pressure only method because any modification of the flue has consequences on all aspects of the pipe operation, whereas the closed-toe method, in connection with higher pressures and with active involvement of cut-up adjustment, allows some separation between sound timbre and power regulation.

Keywords: musical acoustics, aeroacoustics, aerodynamics, resonators, flue organ pipes, pipe organs, pipe voicing, organ building, conservation, fluid mechanics

1 Introduction:

Flue organ pipes are central components of any pipe organ and their sound signature determines its musical qualities and possibilities. This sound is an aeroacoustic side product of a complex flow phenomenon where an inherently unstable and non-linear air jet drives and is driven by an acoustic resonator, thus constituting a feedback system which, under appropriate phase and amplification conditions, can perform stable self-sustained oscillations. Establishing these conditions is the first major goal of the process called pipe voicing, which essentially involves the pipe mouth geometry. Due to the air jet non-linearity and the multiple modes of the pipe resonator, the feedback cycle can lock various harmonically related frequencies into a rich, periodic regime, this being the mechanism which is ultimately responsible for the distinctive, clear sound of sustained musical instruments. The relative amplitudes of the contributions of these different frequencies depends on the specific nature of the interaction of the various parts of the feedback cycle. Usually sufficient degrees of freedom are available to allow many mode regimes and this constitutes the next phase of the voicing process: the establishment of musically desirable regimes. In flue organ pipes the mouth region again is the region where the most distinctive control can be exerted, but there are other, subtle pipe parts which influence the mode mix, such as tuning devices, external objects near the mouth, pipe wall vibration modes,.... In particular the higher modes are involved, those which generate the higher frequency components of the emitted spectrum, to which the human ear is particularly sensitive. Therefore in this phase of the voicing process the underlying physical mechanisms gradually turn into second and higher order phenomena more and more complex to isolate and describe.
Some of the degrees of freedom relate to the air jet formation, specifically to its velocity, aspect ratio and orientation, all of which are basically determined by the flue and the wind pressure in the foot. This paper discusses the various possible jet configurations and the associated flue and toe hole geometries, with the dimensionless parameter $D_{flue/toe}$ to characterize them:

$$D_{flue/toe} = \frac{flue\ area}{toe\ hole\ area}$$

In the past many different values of this parameter have been implemented. Roughly speaking, a temporal evolution throughout organ building history from values <<1, going back into the hazes of the past, to >>1 in the XIXth and early XXth centuries can be observed. This progression is closely associated with a number of developments that influenced organ building:

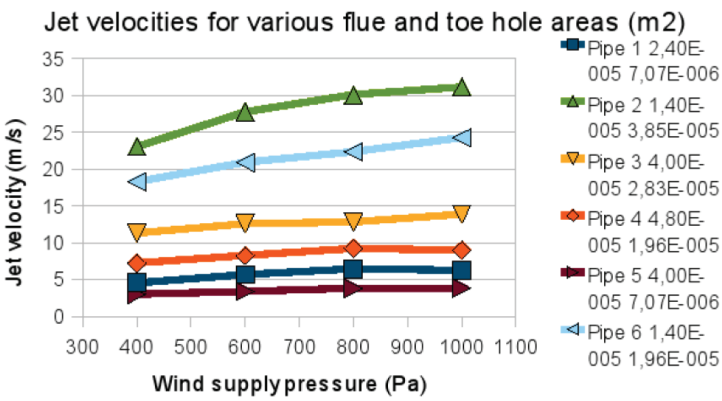
- the way musical taste evolved and accordingly the usage of the pipe organ
- increasing skills and knowledge in the deployment of technology
- the general cultural changes in all fields of society, such as in economy, religion, demography, and so on, often as a result of major events like wars, pandemics or discoveries

These tendencies sometimes could have contradictory influences on organ building, which then imposed the need to find workable compromises. Accordingly, the practice of keeping $D_{flue/toe} \ll 1$, roughly corresponding to the so-called open toe voicing, can be explained from the need to keep wind consumption and pressure as low as possible. Apart from the fact that wind power had to be produced by human effort, wind flow rate had direct influence on the number and size of bellows needed, size of wind channels and pallets and dynamical behavior. Also, wind pressure was relatively low for the sake of the bellows technology, to minimize losses through leaks in leather or through sliding wooden parts, and to keep action forces to acceptable levels. It is now generally understood that there is a close relationship between low wind power instruments and the music made for and on them. Similarly, new developments in musical taste and organ building technology led to the adoption of higher wind power and the possibility to practice voicing with $D_{flue/toe} \gg 1$, the so-called closed-toe voicing techniques. As will be shown further on, closed-toe voicing was particularly adapted to produce industrially designed and produced instruments

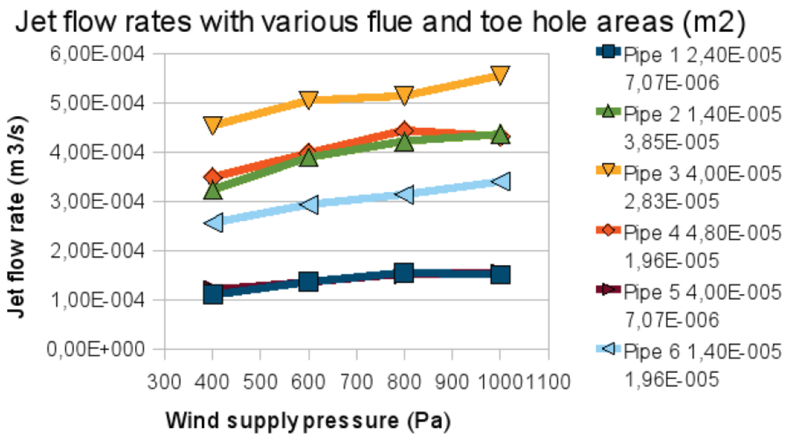
The following analysis of open- and closed-toe voicing methods will focus on some simple steady flow models, starting with the role of flue and toe holes in the characterization of the air jet. Some of the very rare documented historical voicing practices will be discussed in this context. The relationships between toe hole size, foot wind pressure and jet velocity will be experimentally measured using a setup with variable mouth geometry. Results will be compared to measurements made on various pipes in a real pipe rank. For open-toe voicing, the question of over/underblowing regime throughout a pipe rank will be addressed in particular, given the observation that jet velocity regulation is nearly impossible in this case. Finally some remarks will be raised on the influence of the air jet aspect ratio on harmonic development, as well as on the practical aspects and musical implications of both voicing approaches.

2 The dimensionless parameter $D_{flue/toe}$:

The dimensionless parameter $D_{flue/toe}$ has been proposed [Steenbrugge 2010] to quantitatively characterize the influences of flue and tone hole sizes on the voicing process. This proposal is based on a dimensionless analysis of the jet velocity in pipes of various flue and toe hole sizes, fed by wind at different wind supply pressures. Jet velocities measured at the flues of a some arbitrary pipes are shown in the next figure (velocities measured using hot wire anemometry in the middle of the flues, see further down for measurement protocols):



Pipes 1 and 5 have a very constricted toe hole, pipe 2 on the other hand has an open toe and rather narrow flue, pipe 6 has a narrow flue and rather narrow toe hole. Pipes 3 and 4 have wide flues. The respective influence of the flue and toe hole on the jet velocity is not obvious, neither is it on the jet flow rates for the same pipes:

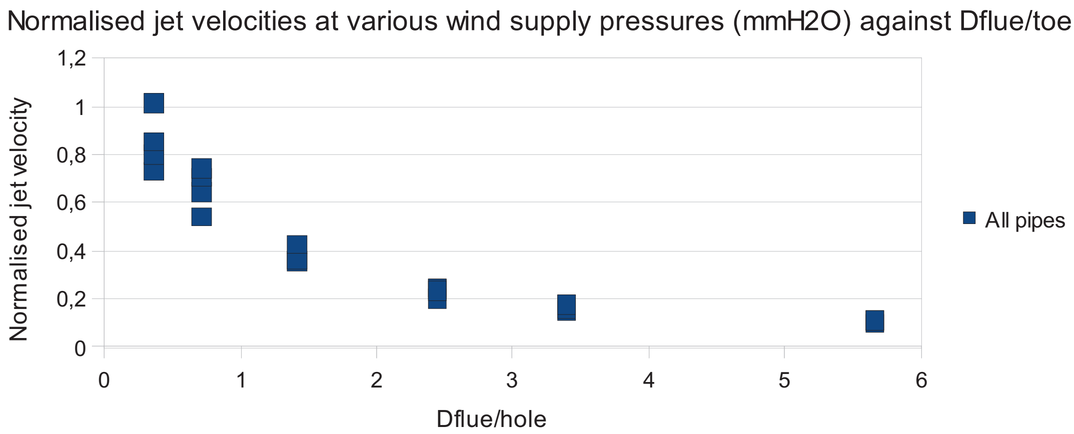


It can be seen that the narrow flue open toe pipe 2 has about the same flow rate as the very wide flue narrow toe pipe 4.at all pressures. Pipes 1 and 5 have about the same flow rate despite widely differing flue widths. Obviously the possible values of flue and toe hole leave many possible combinations of jet velocity and flow rate, both of which have decisive influence on the operating regime of the pipe.
Starting the dimensionless analysis now, the simplest possible dimensionless parameter that incorporates both flue and toe holes is to consider the ratio of their surface area and try to establish a relationship with a dimensionless jet velocity, which is meaningfully obtained by dividing the measured velocities by a velocity that depends only on wind supply pressure, thus eliminating the influence of the latter. This reference velocity V_{supply} can only be:

$$V_{supply} = \sqrt{\frac{\rho P_{supply}}{2}}$$

where:
P_{supply} is the wind supply pressure in Pa
ρ is the air density in kg/m^3

The following figure shows the dimensionless jet velocity as a function of $D_{flue/toe}$ for the same velocity measurements on the same pipes blown at the same wind supply pressures as above :



The observation that the dimensionless jet velocities seemingly collapse to one curve indicates that $D_{flue/toe}$ is the single pipe parameter that completely determines the jet velocity in a flue pipe. In the next section a simple stationary model will be derived to quantitatively describe this behavior.

3 A simple stationary flow model:

For further reference a right-handed coordinate system is chosen with the origin in the middle of the flue edge at the inner side of the lower labium, the x-axis parallel to the pipe axis and positive x-values towards the upper labium.

3.1 Jet velocity – Foot wind pressure relationship:

At the usual wind pressures in flue organ pipes the flow through the flue can be described by considering conservation of energy along a streamline, thereby assuming incompressible, inviscid, and laminar (Re based on flue width ~ 10^2-10^3) conditions and neglecting possible height differences in the gravitational field. Given that the jet is brought to rest downstream of the flue, the following Bernoulli equation applies:

$$P_{foot} = \frac{\rho V^2}{2}$$

Eq. 1

where:
P_{foot} is the foot wind pressure in Pa
V is the jet velocity at the flue exit in m/s
ρ is the air density in kg/m^3

When the jet leaves the flue and this flue consists of a 2D constriction with sharp edges, the jet velocity has a top-hat transversal profile which gradually starts to spread and turns into a so-called Bickley profile [Bickley 1937], the central velocity gradually diminishing in order to conserve jet momentum:

$$V(x, z) = V_0 x^{-1/3} sech^2\left(\frac{z}{b}\right)$$

Eq. 2

where:
V_0 depends on the initial jet velocity V at the flue exit
b is the jet half-width given by:

$$b(x) = b_0 x^{2/3}$$

where in turn:
b_0 depends on the initial jet velocity and the kinematic viscosity of air.

This theoretical profile for a laminar 2D jet is not valid near the flue as it assumes zero flue width. The direction of the jet is determined by the flue geometry.

3.2 Foot wind pressure – Wind chest pressure relationship:

When the toe hole of the pipe is severely constricted, in the sense that $D_{flue/toe} > 1$, the flow through the toe hole experiences a considerable static pressure drop. In a first approximation the toe hole can be modeled as an simple axisymmetric constriction between the wind chest pipe channel and the conical pipe foot. The pressure drop across such an orifice is very sensitive to diameter variations of the constriction but much less to the diameters of the in- and outlet ducts. A usual method to calculate static pressure drop across the constriction again starts from the Bernoulli equation and applies to the result a correction factor, the pressure discharge coefficient C, to take into account the incomplete pressure recovery due to the flow separation:

$$P_1 + \frac{\rho V_1^2}{2} = P_2 + \frac{\rho V_2^2}{2}$$

where:
P_x represents static pressure at point x
V_x represents flow velocity at point x
x=1 is downstream of the orifice and x=2 is at the orifice

The flow rate Q through the orifice is:
$Q = V_1 A_1 = V_2 A_2$
where:
A_x represents the surface area of the duct at point x

The static pressure drop across the orifice ΔP can thus, including the correction discharge coefficient C, be written as:

$$\Delta P = \frac{Q^2 \rho (1-\beta^4)}{2 C^2 A_2^2}$$
Eq. 3

where:
$\beta = A_2/A_1$

C can be experimentally determined or analytical fitting formulae are available in the literature [Idelchik 1984]. For a circular axisymmetric straight-cornered constriction in a circular duct with β<<1, its value is about 0.6 – 0.62.

3.3 Jet velocity dependence on $D_{flue/toe}$:

Combining Eqs. 1 and 3, and assuming β << 1, the jet velocity can be calculated as a function of $D_{flue/toe}$:

$$V = \sqrt{\frac{2P_{supply}}{\rho\left(1 + \frac{D^2_{flue/toe}}{C^2}\right)}}$$
Eq. 4

where:
P_{supply} is the wind supply pressure in Pa

In the case of extreme toe hole constriction the jet velocity formula will be approximately:

$$V = \frac{C}{D_{flue/toe}} \sqrt{\frac{2P_{supply}}{\rho}}$$
Eq. 5

which means that V will monotonously decrease with increasing flue width for any given toe hole size. At the same time however the flow rate, which after all is what provides the necessary driving energy, monotonously rises to a limit value determined by the toe hole size. When the flue width is kept constant, an increase of toe hole diameter obviously leads to a monotonous increase, up to a limit value determined by the wind supply pressure, of both jet velocity and flow rate.
This can be summarized in the following design considerations for the flue and toe hole size, assuming that any change in flue size does not influence jet orientation:
- for any given toe hole area and wind supply pressure, increasing the flue area decreases the jet velocity but increases the jet flow rate
- for closed-toe voicing the flue size has to be large enough that adequate jet velocity regulation is possible with the toe hole and Eq. 5 is valid, say $D_{flue/toe} > 3C$, which means that the flue area must be at least twice the toe area.
- Eq. 4 proves that the jet velocity depends only on $D_{flue/toe}$ and not on the flue and toe hole areas independently.

In practice a number of voicing families can be distinguished based on $D_{flue/hole}$:
- $D_{flue/toe}$ >> 1: what Fisk called 'classical voicing' [Fisk 1976] involves, among other ingredients, a wide open flue and power regulation using the toe hole size. In this method the jet velocity varies along with the regulation, requiring active cut-up adjustments to stabilize operating point.

– $D_{flue/toe}$ << 1: describes the open-toe voicing methods, were jet velocity is kept relatively constant during voicing. So in principle driving power can be regulated by adjusting flue width without influencing the operating point. However, the jet velocity profile is modified in sharpness and possibly in orientation, influencing pipe speech and timbre.

– $D_{flue/toe}$ ~ 1: in this region both flue and toe hole are adjusted in such a way that $D_{flue/toe}$ varies less than the previous methods, thus somewhat avoiding their inconveniences. However this method requires fine fitting of both parameters. This method was practiced by classical late Baroque builders such as Gottfried Silbermann, in later periods the method was adopted by Schulze in the XIXth century, who used it with very large areas at relatively low wind supply pressures, leading to his typical impressive flue plena.

4 Experiments:

In this section the model discussed so far to describe open- and closed-toe voicing will be verified through jet velocity and foot pressure measurements on real pipes and an experimental pipe setup which allows continuous and precise adjustment of the voicing parameters involved.

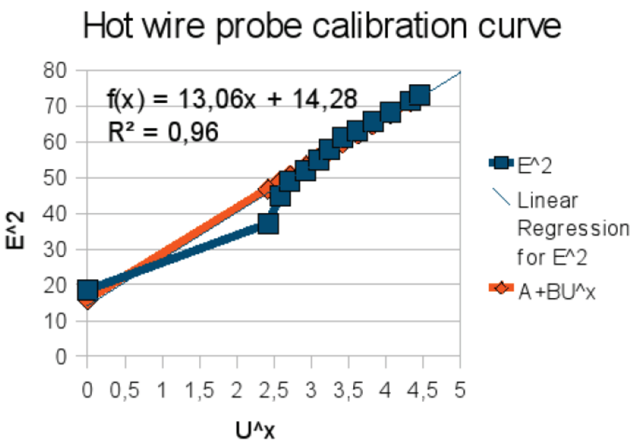
4.1 Method:

Jet velocities were measured using Constant Temperature Anemometry (CTA), allowing to measure air velocity magnitudes with very high spatial resolution in a plane perpendicular to the wire of a hot wire probe. Accordingly, the measurement plane was the y=0 plane. This wire, made of platinum coated tungsten, is 5µm in diameter and 1.5mm long, and is welded to 2 needle-shaped supporting prongs which also supply the heating current. The following picture shows the hot wire next to a human hair at 50x magnification:
The probe is mounted on a x-z traverse mechanism which allows the hot wire to reach any position in the measurement plane, movement step size is 30µm. It is not possible to measure velocity directions with this single hot wire probe, but from a measured velocity magnitudes field, assumed 2D, and using mass conservation considerations, velocity vectors could be calculated.
The experimental pipe set-up used will not be described in detail here, suffice it to say that the experimental pipes, through their specific geometry, allow continuous and precise step-motor controlled adjustment of toe hole area, flue width, cut-up and upper labium offset (by movement of the resonator along the z-axis). Step sizes are 30µm. The wind is supplied by a wind chest with adjustable pressure and electromagnet controlled pallets. The flue geometry is formed by a straight-cornered lower labium and a sharp edged nickless languid 3mm thick and with a 66° bevel. The languid and the lower labium edge, defining the flue exit, are both located in the x=0 plane and at all times parallel to each other (+/- 50µm).
Calibration of each probe is done by a calibrating wind tunnel, which produces a low turbulence air jet. The probe is mounted into the jet at the exit from the tunnel, a range of jet velocities corresponding to the measuring range is successively generated and the static pressure inside the stagnation chamber of the wind tunnel measured. The non-linear correspondence between the air velocity and the hot wire heating power is, in CTA, given by King's law:

$$E^2 = A + BU^x$$
Eq. 6

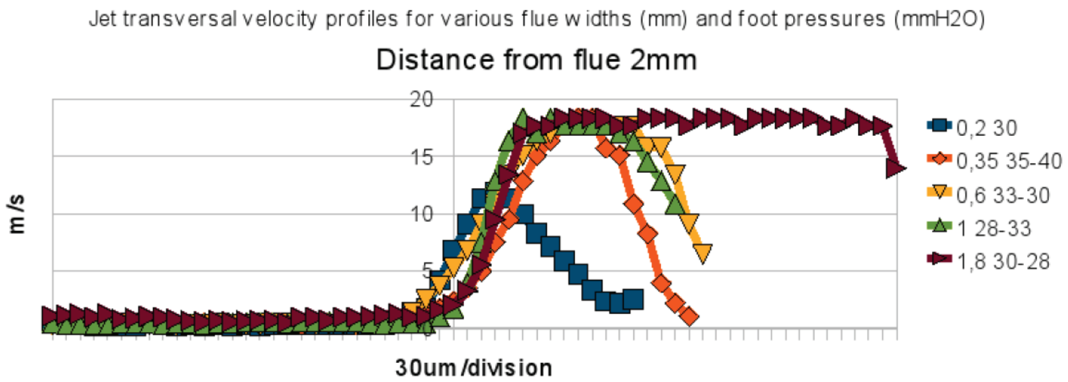
where:
E is the voltage at the CTA bridge
U is the air jet velocity
A and B are constants to be determined in the calibration
x is a value between 0.45 and 0.5, to be determined in the calibration

The figure on the right shows a typical calibration curve.
At low but non-zero velocities the simple calibration procedure described above is no longer accurate enough, King's law however remains valid.

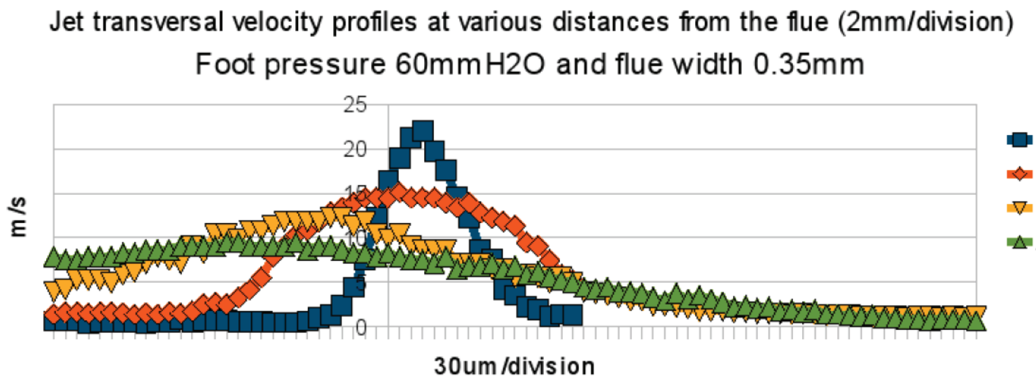


4.2 Jet velocity profiles:

The following figure shows jet velocity profiles, measured at 2 mm distance from the flue exit for various flue widths. The pipe resonator was muted in order to prevent the jet to be disturbed by an acoustic field. Due to a small backlash condition in the traverse mechanism the linear displacements have an absolute error of +/- 2 stepsizes. The position of the y-axis indicates the outer flue edge location:



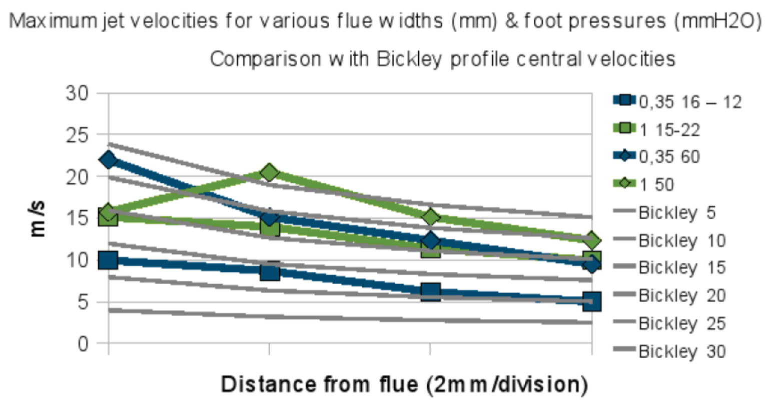
During this preliminary measurement foot pressure variations of up to 10% occurred due to a minimal mechanical coupling between traverse mechanism and the flue width control system, causing slight velocity variations up to 3%. Towards the right of the chart, moving towards the inside of the pipe, the measurement range was limited by the languid bevel. The wider flue widths clearly show the top-hat velocity profile, whereas the narrower widths already have a Bickley profile. All measurements were done in the same foot pressure range, with less than 20% difference between upper and lower values, and accordingly it is observed that, with the exception of the narrowest flue, all flue widths give similar jet velocities. This confirms the wide validity of Eq. 1 applied to the jet sufficiently close to its exit, long before it becomes fully developed or breaks down in vortices (which was not the case for the narrowest flue in this measurement). The following figure shows transversal jet velocity profiles at various distances from the flue:



The velocity profile spreads and, in accordance with conservation of jet momentum, the central velocity gradually decreases. In the next figure the central velocities at various heights are compared to the theoretical Bickley values for some flue widths and foot pressures:

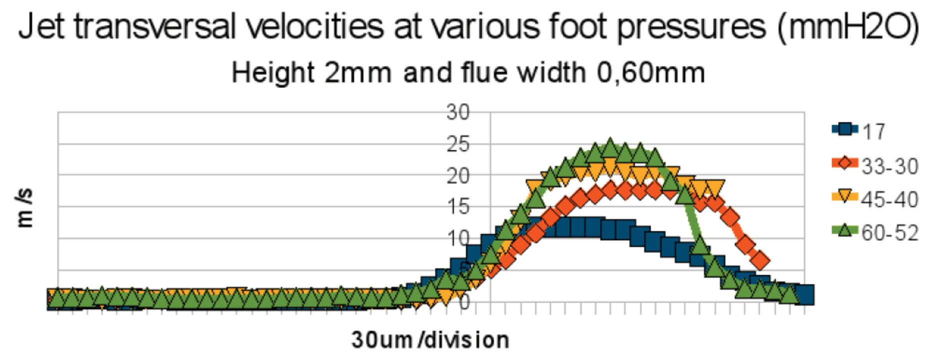
Apart from an obvious erroneous measurement, there are 2 main deviations:

- the languid bevel influences the jet flow, especially at the distances close to the flue and especially at lower velocities, due to recirculation between the jet and the languid bevel and possibly to Coanda effects. As a result the velocities at the first 2 stages are increased



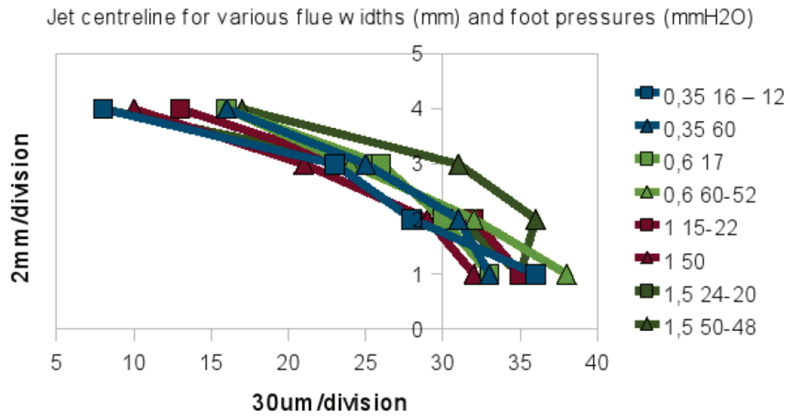
– at higher pressures the velocity decreases more rapidly than the Bickley law, possibly due to the jet flow going fully turbulent.

The next figure shows jet transversal velocities for various foot pressures:



By following the locus of maximum measured jet velocity with increasing distance from the flue, it is possible to somehow reconstruct the jet trajectory. These locii are thus taken as the centerline of the jet, as shown in the following figure:

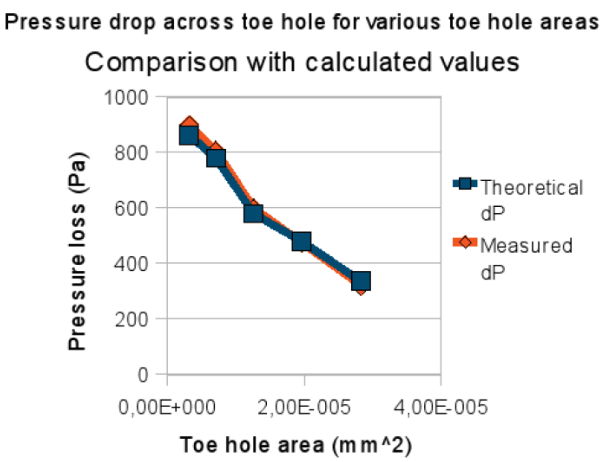
The general conclusion to be drawn from this figure is that the jet flow direction, in the geometry used for these measurements, is rather insensitive to either pressure variations or, surprisingly, to flue width variations.



4.3 *Pressure drop measurements across the toe hole:*

The differential pressure between static wind supply and foot pressures was measured in an experimental pipe for various toe hole diameters and corresponding flow rates. The flow rates were calculated from the simultaneous measurement of the air jet velocity.

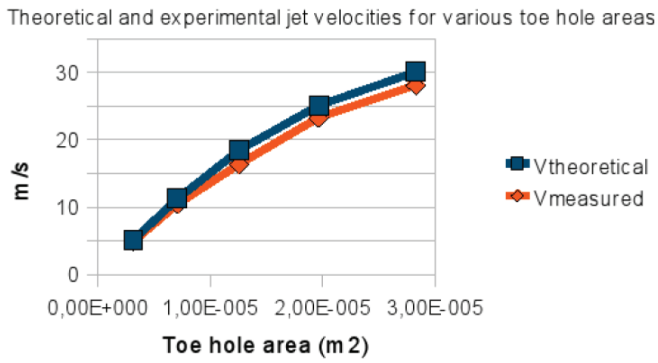
The following figure shows the pressure drop as a function of toe hole diameter at a constant wind supply pressure of 950 Pa, a flue width of 0.35mm and length of 0,04m. In the same figure the pressure drops calculated from Eq.3 are shown:



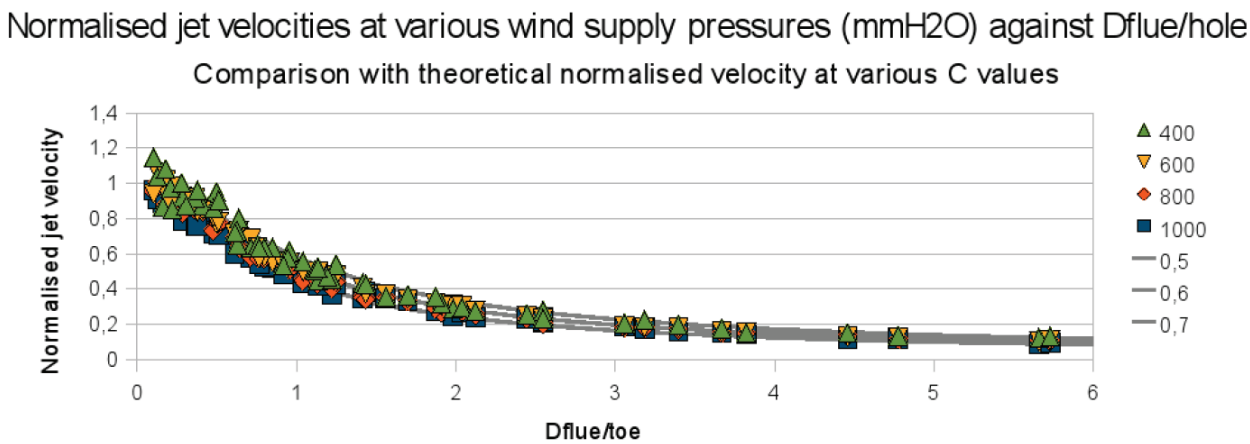
The correspondence between measured and calculated values drops down for low β values where the toe hole no longer behaves like a simple straight-cornered orifice.

4.4 Jet velocity measurements for varying toe hole diameter:

Eq. 4 can be experimentally verified using any flue pipe on condition the toe hole geometry sufficiently approximates an axisymmetric straight-cornered orifice. The figure to the right shows jet velocities corresponding to the measuring points from the previous figure:



Next, a large series of velocity measurements was done on an experimental pipe with automatically controlled step-wise change of flue width and toe hole areas, and wind supply pressure as the third parameter. All these parameters were varied over a range encompassing all possible situations in flue pipes. The next figure shows all velocities obtained, normalized using the corresponding pressures, as a function of the corresponding $D_{flue/toe}$:



Again the collapse of the normalized velocities shows a dependence of the jet velocity on $D_{flue/toe}$ only. Deviations are mainly attributed to variations in C for different toe hole areas due to the specific construction of the variable toe hole.

4.5 Jet velocities and cut-up in a closed-toe voiced pipe rank:

It's interesting to calculate the mouth transit time parameter D_{mouth} in real closed-toe voiced pipe ranks using measured jet velocities, in order to:

- check whether the jet velocity calculation yields realistic values
- determine whether the way flue and toe hole are voiced so as to be consistent with the cut-up and the corresponding voicing determinant D_{mouth}, defined as:

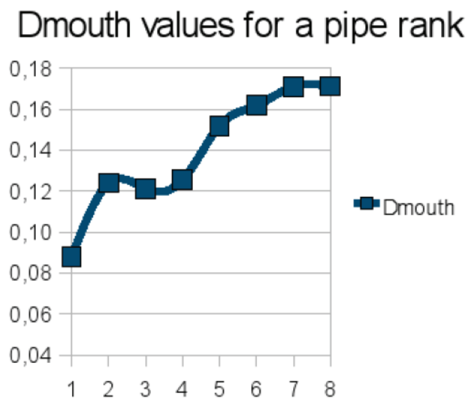
$$D_{mouth} = \frac{fl}{V}$$

where:
f is the fundamental frequency of the sounding pipe
l is the cut-up

The following data are measured on a rank of principal pipes [Steenbrugge 2005]:

Montre 8’	Diameter (cm)	Flue length (cm)	Cut-up (cm)	Toe hole diameter (mm)	Flue width (mm)
C					
G					
c	8,50	6,80	1,67	11,00	1,10
g	6,10	5,10	1,24	7,70	1,00
c^1	5,35	4,13	1,00	7,00	0,90
g^1	4,23	3,25	0,73	6,10	0,80
c^2	3,53	2,70	0,67	5,60	0,80
g^2	2,72	2,10	0,53	5,20	0,75
c^3	2,30	1,70	0,37	4,10	0,70
g^3	1,72	1,30	0,31	4,00	0,60

The figure to the right shows the calculated D_{mouth} values for this rank, blown with 850Pa wind pressure:



These are normal values for D_{mouth}, lying around 1/8, with a normal tendency to rise due to the fact that the cut-up, as can be seen in the table, does not scale like f^{-1} but scales with the diameter and thus becomes relatively high in the treble. $D_{flue/toe}$ thus generates realistic values for D_{mouth} , although some irregularities remain in its progression throughout the range. Experimental verification of the actual jet velocities is not yet available for this pipe rank.

5 The open-toe voicing problem:

In open-toe voicing the air jet's aspect ratio is the only variable in the air jet wind supply that can be controlled allowing -by a changing flow rate- to adjust the power supplied to the pipe. However, besides providing this pneumatic power, the air jet, through its aerodynamic properties, also serves to build and maintain the feedback loop necessary for oscillation and these influences are necessarily modified at the same time.

5.1 Cut-up:

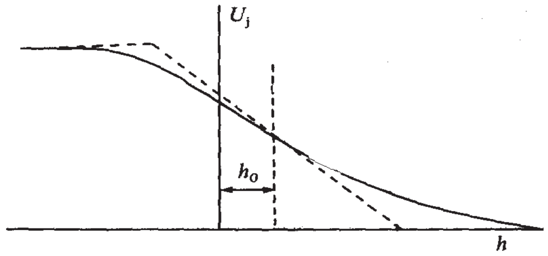
In contrast to closed-toe voicing, the previous experiments lead to the hypothesis that in open-toe voicing jet velocities are essentially constant throughout the pipe rank. As the jet transfer time to oscillation period parameter D_{mouth} is bound to certain limits in order to allow self-sustained oscillation, this would imply that l necessarily scales like f^{-1}, although in usual practice l is always considered to be a constant fraction, around 1/4 of mouth width (see for example the data of the pipe rank studied above), itself being a constant fraction of the pipe diameter (ibidem), which scales like f^{-x}, with x approximately equal to ¾. This raises the question whether in practice open-toe voicing is rigorously applied throughout a complete pipe rank with a frequency range of at least 4 octaves (that is with all foot pressures equal).

5.2 Jet orientation:

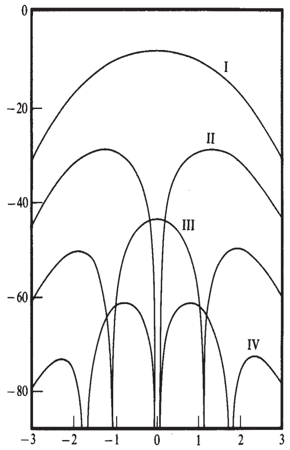
In the case of metal pipes and wooden pipes without a flue channel, the jet orientation depends on minor variations in the flue geometry, essentially the relative position and shape of the two edges defining the flue. Changing the relative position of both in the direction parallel to the jet flow direction, or in other words, changing the direction of the flue exit surface (normally a plane if the edges are parallel), may alter the jet orientation. If the flue width is changed in such a way that this flue exit surface is reoriented, the jet direction can change.

5.3 Jet velocity profile:

As observed in the previously mentioned jet velocity profile measurements, changing the flue width at the flue exit changes the velocity profile width all along the jet. This influences the way the jet drives the resonator modes, as illustrated in the next figure [after Fletcher&Rossing 1998], which shows the jet flow rate U_j into the resonator as a function of jet deflection h -in the z-direction- at the upper lip:



In the figure h_0 is the upper lip offset from the jet symmetry plane at the upper lip height, and b the jet half-width. The interrupted broken curve shows the flow rate in the hypothetical case of a top-hat velocity profile, the jet width 2b is the distance between the abscissa of the breaks in the curve. It can be deduced that the smaller b, the more the flow rate will have a square wave appearance in time, and thus strongly drive the harmonic modes because most of the time it will be saturated to one of the edge sides. The asymmetry resulting from the upper lip offset h_0 also determines the proportion in which the various harmonic modes will be driven. The influence of both b and h_0 on harmonic drive is summarized in the figure on the left [Fletcher&Douglass 1980], were the calculated relative amplitudes of the first 3 harmonics are plotted as a function of b/h_0.



Experiments are currently under way to find answers to the following issues regarding open-toe voicing::
1. Jet velocity – cut-up relationship in open-toe voiced pipe rank:
In order to characterize an existing open-toe voiced pipe rank, jet velocities and a number of scales - diameter and cut-up- will be measured. As in the previously discussed closed-toe case, specific attention will be given to the progression of D_{mouth} throughout the rank. It is possible that jet orientation plays an important role in this way of voicing, in that a very precise adjustment of the jet flow angle might allow the pipe to establish the feedback loop at a lower velocity than the central jet velocity, thus avoiding the pipe to overblow right from the start and thus in fact extending the range of D_{mouth} within stable speech is possible.
2. Jet orientation dependence on flue width:
More experiments with various flue geometries must be done in order to assess their impact on the jet orientation. The preliminary transversal jet velocity measurements presented and discussed higher however seem to indicate that jet orientation is not particularly sensitive to flue width for the most usual geometries. This point needs more specific experimental setups to be exhaustively tested.
3. Jet harmonic drive dependence on flue width:
Following the theoretical outline given above experiments will be done to establish links between jet velocity profiles, jet flow rates and acoustic output.

6 Discussion and conclusion:

The relevance of the $D_{flue/toe}$ voicing determinant was established through dimensionless analysis and through the construction of a simple stationary flow model were it plays a central role in determining the jet velocity. This determinant allows to characterize a number of voicing methods involving flue width and toe hole size. It was shown however that each of these methods has specific implications on other voicing parameters: closed-toe voicing involves active adjustment of the cut-up, whereas open-toe voicing is expected to require very precise languid control in order to allow stable speech.
Closed-toe voicing can be considered as an easier method than open-toe voicing because it offers more degrees of freedom, allowing to control various aspects of the air jet. A certain amount of pressure loss at the toe hole has to be taken for granted and wide flues can generate unfavorable sizzling sounds which are minimized by nicking the languid. Due to a somewhat wider air jet the sound is usually rounder. The availability of more degrees of freedom allows to specialize one for power regulation (the toe hole) and another for the timbre (the flue). The latter can be set in the factory during the so-called pre-voicing, the former can be adjusted in situ when establishing the tonal balance, with possibly minor cut-up modifications. Open-toe voicing involves adjusting the air jet with control parameters that strongly influence each other. Therefore it can only be performed on site and in a carefully deployed process requiring delicate and patient manipulation. The result can be a genuine lively and more or less irregular sound giving every

pipe a strong individuality of its own.
As stipulated above, further experimental work will be done to verify the open-toe voicing hypotheses made. Furthermore extensive measurements will be done on existing pipe ranks to test the robustness of $D_{flue/toe}$ as a tool to quantitatively describe flue width and toe hole voicing.

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