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By W. E. A. MAHU[1], M. C. A. M. PETERS[1], M.-P. VERGE[2], A. P. J. WIJNANDS[1], B. FABRE[3], and A. HIRSCHBERG[1]

[1]Technische Universiteit Eindhoven, W&S 0.54, Postbus 513, 5600 MB Eindhoven, The Netherlands

[2] I.R.C.A.M., 1, Place Igor Stravinski, 75004, Paris, France

[3] Laboratoire d'acoustique musicale, C.N.R.S. U.R.A. 868, Université de Paris VI, Tour 66, 4 Place Jussieu, 75252, Paris, France

Flow visualizations of the jet formation during the initial phase of the attack transient in a flue organ pipe are presented. These visualizations are related to acoustical pressure measurements inside the pipe. This acoustical response appears to be extremely sensitive to the steepness of the rise of the supply pressure in the foot of the pipe. A fast pressure rise implies not only a strong initial pressure buildup due to the volume injection, it also results in an impulsive vortex shedding at the labium when the jet reaches this sharp edge. For a slow pressure rise the initial response is considerably smaller and the jet is so strongly deflected outwards that it initially misses the labium. These observations are analysed and related to the effect of the labium position and to the use of ears on the attack transient of organ pipes.

1. Introduction

Physical models of musical instruments can be used to develop a new type of sound synthetisers. Models for various instruments are available at IRCAM†. The work presented here is a contribution to the development of physical models of flute-like instruments. In these instruments the sound is obtained by the interaction of an air jet with a sharp edge, called the labium. The jet is formed by blowing through a channel, called the flue, or by using the lips. The details of the sound production are not fully understood. The instrument is usually modelled as a feedback loop consisting of a linear amplifier, the jet, which is non-linearly coupled to a resonator, represented as a linear acoustical filter. Models of this type described in the review of Fletcher and Rossing (1991) appear to be unable to describe simple features such as the steady-state acoustical amplitude. The non-linearity of the jet flow into the pipe, due to saturation when the jet displacement at the labium becomes larger than the jet width, is unable to predict the right amplitude and the specral distribution of higher harmonics. As discussed by Fabre (1992) the vortex shedding at the labium has to be taken into account to explain the experiments. This corresponds to the amplitude dependence of the mouth "pseudo impedance" reported by Coltman (1968).

While the steady oscillation of the instrument is not fully understood, the attack transient has not even been investigated systematically. The works of Castellengo (1976), Angster and Miklos (1989) and Nolle (1992) show a great variety of attack

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transients. The importance of the attack transient for the perception of sound justifies a much more detailed study.

It is surprising that in the few existing theoretical studies of the attack transient (Nolle (1992), Fletcher (1976)), a quasi-stationary model of the jet flow is assumed. The jet is assumed to be formed instantaneously and to have a steady volume flux Q_j determined by the supply pressure p_0 in the foot of the pipe. The sound production is assumed to occur by volume injection into the pipe at the labium. The possibility of a time dependent jet flux Q_j resulting in a monopole sound source at the flue exit has been overlooked in the studies of Fletcher and Nolle. In this paper we compare acoustical pressure measurements p_1 at the pipe wall facing the mouth with theoretical calculations described in more detail by Verge *et al.* (1993). In these calculations a low frequency approximation is used and the interaction with the labium is ignored. We simply consider the effect of the time dependence of Q_j. Furthermore we present some recent flow visualizations and numerical calculations of the flow.

2. Experimental procedures

The geometry of the flue organ pipe used for our experiments is shown in figure 1. For reasons of simplicity, the geometry has sharp edges and a straight flue channel. The flue channel height h is one millimeter. The labium has been placed at a distance $4\,h$ from the flue exit at a level $0.2\,h$ (pipe-inwards) below the symmetry plane of the flue channel. The labium angle is sharp and has an angle of 15°. These features are characteristic for a recorder. The mouth width is equal to the pipe width. The pipe has a square cross section of surface $S_p = 400$ mm^2. The mouth surface is $S_m = 80$ mm^2 and the flue channel cross section is $S_c = 20$ mm^2. The pipe is open at its passive end and has a length $L = 283$ mm.

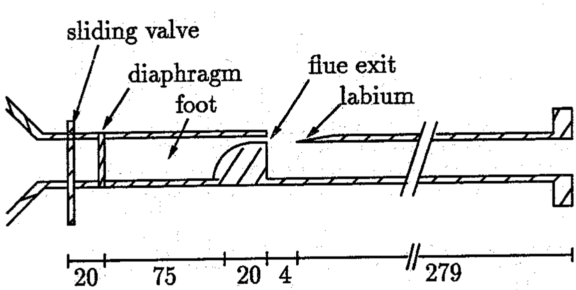

FIGURE 1. Pipe geometry.

This results in a fundamental resonance frequency $f_0 = 514$ Hz. The visualization is obtained with a Schlieren technique. The refractive index contrast is provided by injecting CO_2 in the foot of the pipe. The air flow is initiated by opening a valve placed just upstream of the foot of the pipe. The valve can be opened mechanically for a steep pressure rise (0.5 ms) or manually for a smoother pressure rise (10 ms). Pressure histories measured in the foot p_0 and at the pipe wall facing the mouth p_1, are presented in figures 4 and 5.

For the steep pressure rise, we observe after 6 ms of noise due to the friction of the valve (before opening) a complex oscillation dominating the signal during the first

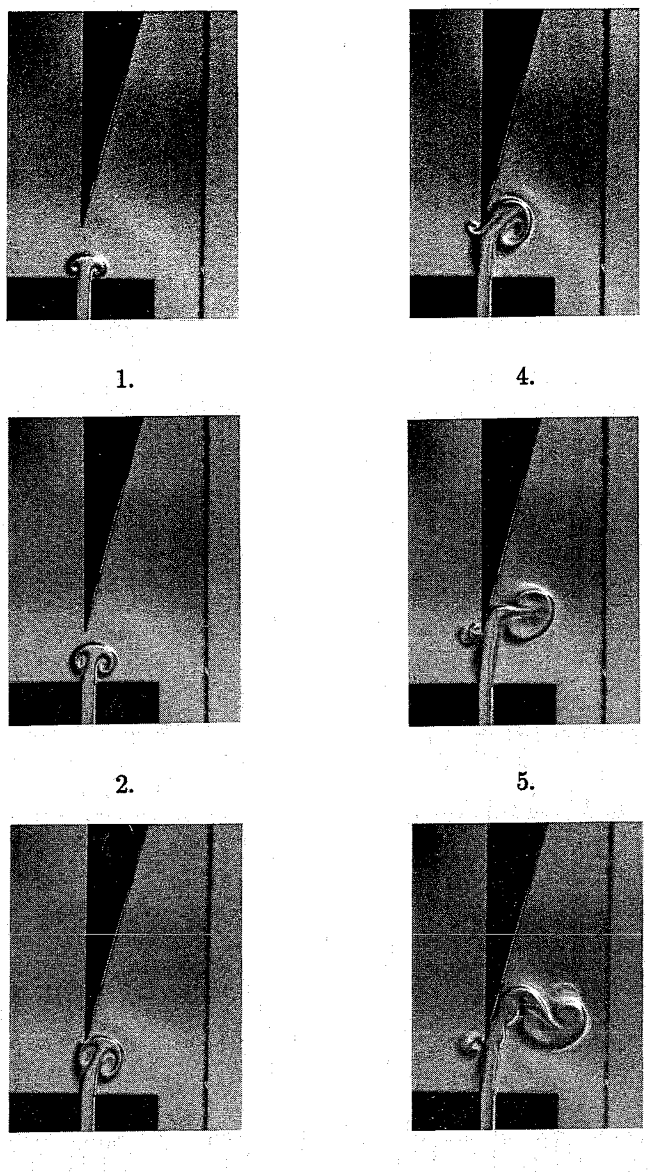

FIGURE 2. Flow visualizations for a fast valve opening, corresponding to the pressure data given in figure 4. Time t given after valve opening: $t_1 = 1.69$ ms, $t_2 = 1.98$ ms, $t_3 = 2.49$ ms, $t_4 = 3.03$ ms, $t_5 = 3.50$ ms, $t_6 = 4.13$ ms.

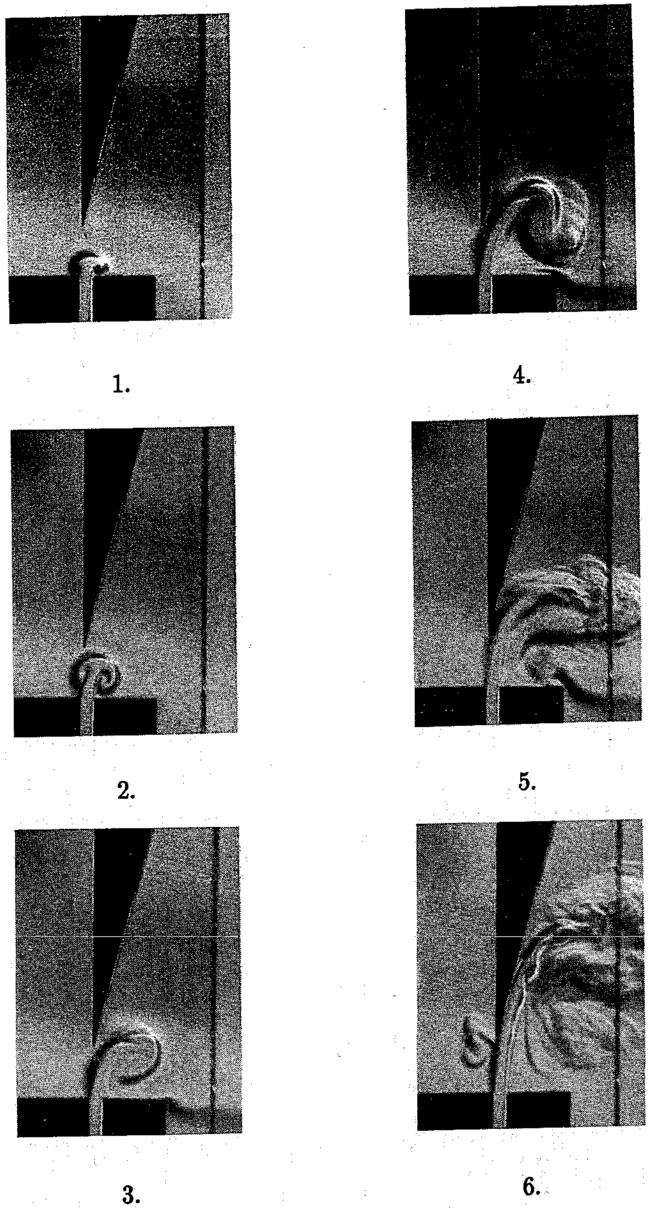

FIGURE 3. Flow visualizations for a slow valve opening, corresponding to the pressure data given in figure 5. Time t given after valve opening: $t_1 = 2.50$ ms, $t_2 = 4.00$ ms, $t_3 = 5.50$ ms, $t_4 = 7.00$ ms, $t_5 = 8.50$ ms, $t_6 = 10.0$ ms.

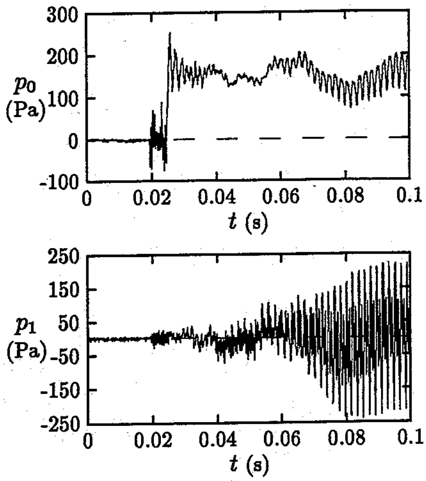

FIGURE 4. Foot pressure p_0 and pipe response p_1 for the fast valve opening.

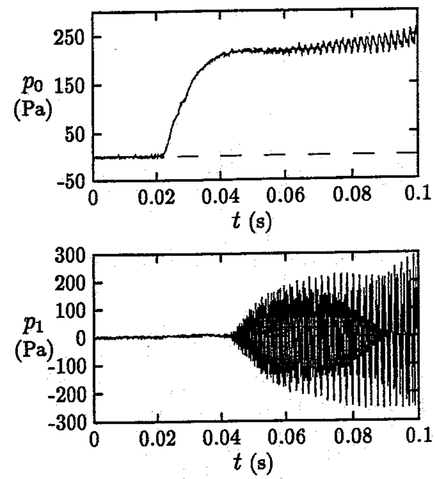

FIGURE 5. Foot pressure p_0 and pipe response p_1 for the slow valve opening.

40 ms before steady oscillation is reached. In the case of a slow attack, we observe only a very faint initial response during the first 10 ms, followed by an exponential growth of oscillations of the third mode of the pipe at a frequency close to $3f_0$. After about 40 ms saturation occurs and the oscillation frequency shifts towards the fundamental mode f_0. Striking differences between the flow induced by the two pressure rises are observed in the visualizations (figures 2 and 3). In the case of a fast attack, the jet hits the labium after about 2 ms resulting in an impulsive vortex shedding at the labium followed by a varicose type oscillation of the jet. In the slow attack, the jet initially misses the labium. The contact between the jet and the edge of the labium is only established after 10 ms, corresponding roughly to the delay in pipe response observed in figure 5. In both cases the jet is clearly deflected outwards before it reaches the labium.

3. Theoretical analysis

We will now present a simplified model of this initial behaviour. A more detailed model is proposed by Verge *et al.* (1993). As a starting point for our analysis we note that the mouth dimensions $\sqrt{S_m}$ and the flue channel length are small compared to the distance $c_0\tau$ of propagation of acoustic waves corresponding to the typical rise times $0.5 \text{ ms} \leq \tau \leq 10 \text{ ms}$. We can therefore locally neglect the effects of compressibility and assume that the jet volume flux Q_j is equal to the sum of the flow Q_{out} leaving the pipe and the flow Q_{in} entering the pipe: $Q_j = Q_{\text{out}} + Q_{\text{in}}$ (figure 6). If we ignore friction and neglect non-linear terms, which is valid as long as the flow is dominated by the inertia, the equation of Bernoulli applied from the foot of the pipe to the flue exit yields:

$$\rho_0 \frac{l_c}{S_c} \frac{\partial Q_j}{\partial t} \simeq p_0 - p_m, \tag{3.1}$$

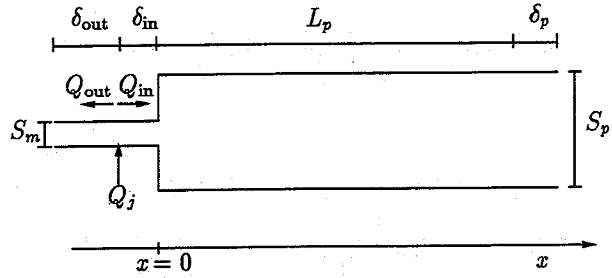

FIGURE 6. Acoustical model of the pipe.

where l_c is the effective channel length ($l_c = 27$ mm), ρ_0 the air density and p_m the mouth pressure. The pressure p_m is related to Q_{out} by:

$$\rho_0 \frac{\delta_{\text{out}}}{S_m} \frac{\partial Q_{\text{out}}}{\partial t} = p_m, \tag{3.2}$$

where δ_{out} is the end correction representing the inertia of the flow at the mouth exit. Measurements discussed by Verge *et al.* (1993) show that $\delta_{\text{out}} \simeq 6$ mm. The pressure p_1 at the transducer placed at the pipe entrance is related to p_m by:

$$\rho_0 \frac{\delta_{\text{in}}}{S_m} \frac{\partial Q_{\text{in}}}{\partial t} = p_m - p_1, \tag{3.3}$$

where $\delta_{\text{in}} \simeq 3$ mm. Furthermore for times t such that if $(f_0 t) < 1$ we have no reflections from the passive pipe end and:

$$p_1 = \rho_0 c_0 \frac{Q_{\text{in}}}{S_p}. \tag{3.4}$$

Assuming that $\partial Q/\partial t \simeq Q/t$, we have from equations (3.2–3.4):

$$\frac{Q_{\text{out}}}{Q_{\text{in}}} \simeq \frac{\delta_{\text{in}}}{\delta_{\text{out}}} + \frac{c_0 t}{\delta_{\text{out}}} \left(\frac{S_m}{S_p} \right), \tag{3.5}$$

hence because $(S_m/S_p)(c_0 t/\delta_{\text{out}}) > 1$ for $t > 0.1$ms in our experiments we can assume $Q_{\text{out}}/Q_{\text{in}} \gg 1$, so that $Q_{\text{out}} \simeq Q_j$ and $p_m \simeq p_1$. The dominance of the outflow for $t \geq 0.1$ms explains the initial bending of the jet towards the exterior of the pipe observed in the visualizations (figures 2 and 3). Furthermore using the approximation $Q_{\text{out}} \simeq Q_j$ and equations 3.1 and 3.2 we find:

$$\frac{p_0}{p_m} = 1 + \frac{l_c}{\delta_{\text{out}}} \left(\frac{S_m}{S_c} \right) \tag{3.6}$$

hence $p_0/p_m \simeq 18$ which appears to be a reasonable approximation for the first 2 ms of the pipe response shown in figure 7.

The use of ears around the mouth of an organ pipe and the large wall thickness of a recorder at the mouth result into a large δ_{out}. This implies a strong initial pipe response p_m/p_0 and a relatively small $Q_{\text{out}}/Q_{\text{in}}$. Hence the jet is forced by the ears to follow a straighter trajectory thereby increasing the chances that it will hit the labium early in the transient. The same effect could be obtained by placing the labium higher, more pipe outwards. The displacement of the labium will however dramatically influence the ratio of even and uneven harmonics in the steady sound (Fletcher and Rossing 1991). Ears therefore allow the use of a low labium (rich sound).

In figure 7 we show the response of the pipe p_1 calculated by Verge *et al.* (1993). In these calculations the interaction of the jet with the labium has been ignored. Higher pressures have been used than in figures 4 & 5 because of the more apparent transient in this case. We clearly observe a deviation between theory and experiment just when vortex shedding at the labium is observed in the corresponding visualization. A more detailed analysis including the effect of vortex shedding at the labium necessitate a detailed numerical simulation of the flow. Calculations based on the vortex blob method (Krasny 1987) have been carried out in collaboration with the team of Prof. Piva. In these preliminary calculations the flux Q_j was calculated from the measured pressure p_0 by using the equation of Bernoulli neglecting the pipe response ($p_m \simeq 0$). The ratio Q_{out}/Q_{in} was further calculated using the approximation given by equation (3.5).

The blob diameter was taken to adjust the typical thickness of the unsteady viscous shear layers in the flue channel ($\delta_v/h = 0.35$ and 0.5). The flue channel h was reduced by a corresponding displacement thickness. We see from figure 8 that the numerical calculations qualitatively predict the observed flow. Further work is now undertaken to include the observed phenomena in a simplified model suitable for time domain calculations.

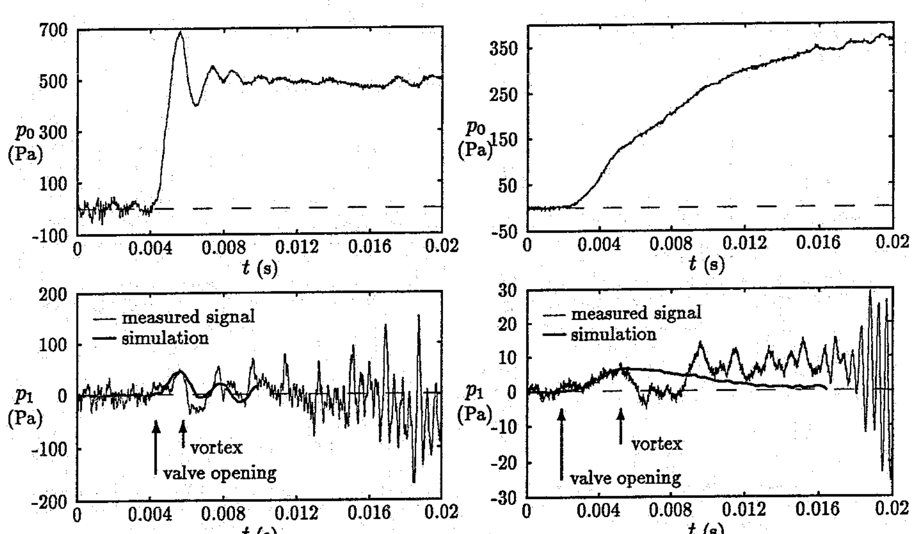

FIGURE 7. Comparison of the pipe response p_1 to the calculated response due to the unsteady volume injection Q_j in the pipe at the flue exit for given foot pressure p_0.

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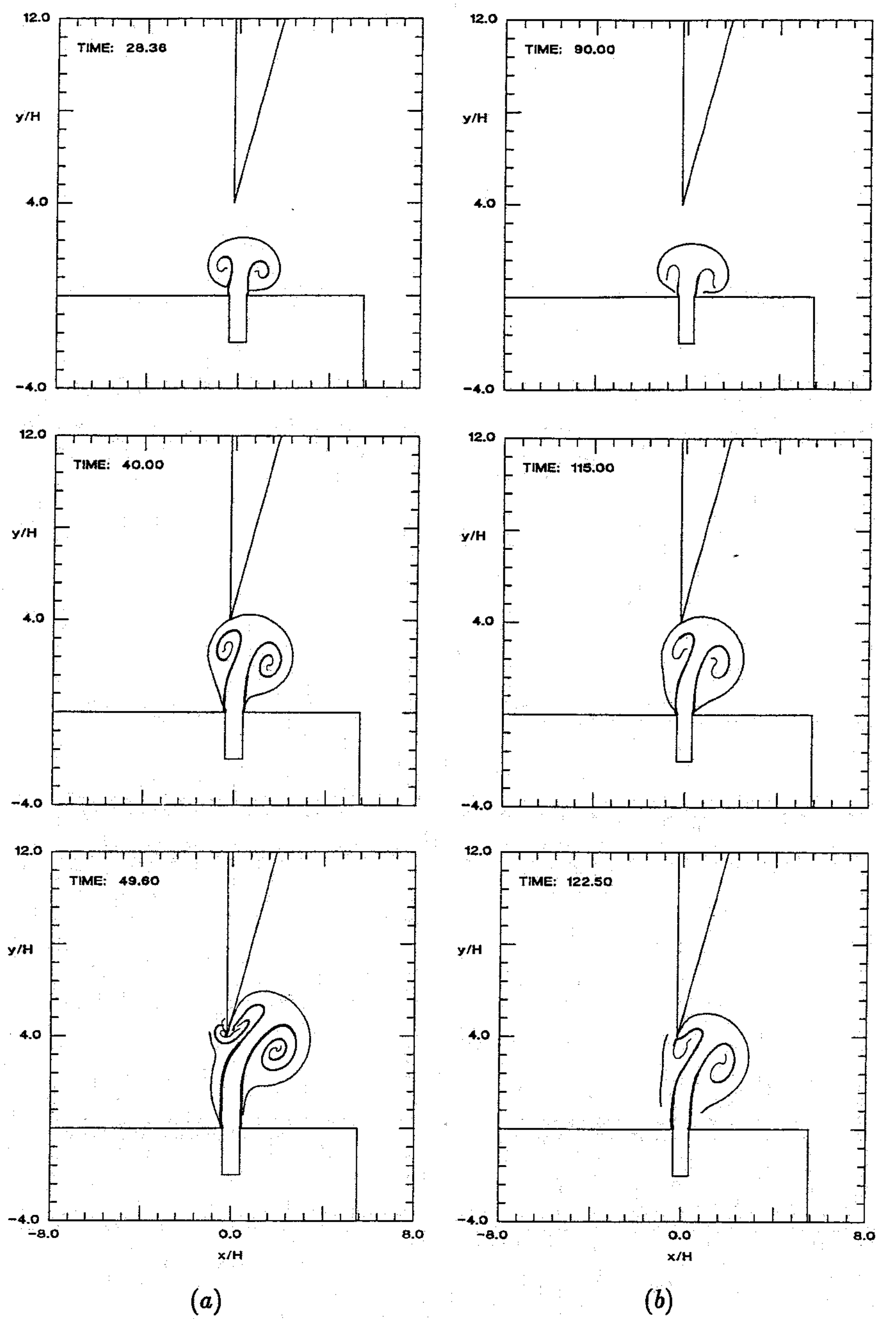

FIGURE 8. Flow simulations. (a) Corresponding to the fast valve opening: $Q_{\rm out}/Q_{\rm in}(t) \simeq (\delta_{\rm in}/\delta_{\rm out}) + (c_0 t/\delta_{\rm out})(S_m/S_p)$. (b) Slow valve opening: $Q_{\rm in}/Q_{\rm out} = 0$. The given times were made dimensionless using the statinary Bernoulli velocity and the flue exit height h.