Fluidic Oscillators and their Applications

Fluidic Oscillators and their Applications

By

Václav Tesař

Cambridge Scholars
Publishing

Fluidic Oscillators and their Applications

By Václav Tesař

This book first published 2024

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-0364-0660-1
ISBN (13): 978-1-0364-0660-8

TABLE OF CONTENTS

CHAPTER 1

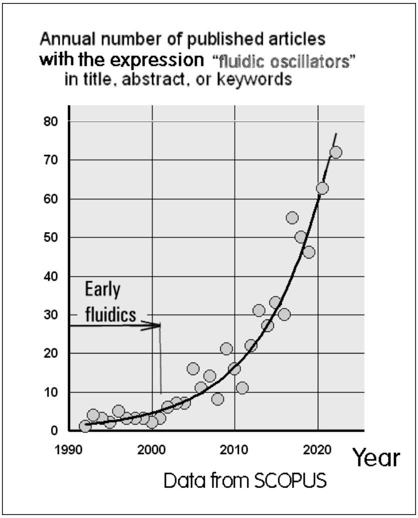
PERIODICALLY VARIEDFLUID FLOWS

1.1 Importance of fluidics

In this monograph, three closely related main subject themes are discussed:

(a) oscillating fluid flows and their character
(b) oscillators as devices for oscillation generation, and
(c) uses of fluidic oscillators in applications.

So far, in the literature there is no such publication containing an overall discussion of fluid flow oscillation from the point of view of fluidics. This applies especially to ***fluidic oscillators***: devices characterised by the small size of their moving or deformed components interacting with the fluid flow. Nor is there an extensive discussion of pure fluidic oscillators which have no mechanical components at all. The small inertia of these objects makes very high oscillation frequencies possible. Pure fluidic devices operate by using fluid dynamics phenomena generated in a specially shaped cavity inside the oscillator body. This absence of any mechanisms brings numerous advantages, such as inexpensive device fabrication, a long working life, attainment of very high oscillation frequencies, and resistance to aggressive or dangerous working fluids. The term '*fluidics*', by which the devices discussed here are known, is of relatively recent origin. It was introduced in the 1960s in analogy to '*electronics*' – the similar technique of the generation and handling of electric currents which, at about the same time, underwent an analogous development in handling fluids, from relays with moving parts to semi-conductors. The term "fluidics" also has a general connotation. It emphasises the handling of both liquids and gases. It also involves two-phase mixtures of liquid with gas (e.g., containing it as bubbles). Fluidics also has the capability to perform, by engineering methods, the fluid flow control actions of living organisms. Thus, fluidics is increasingly becoming a part of biotechnology.



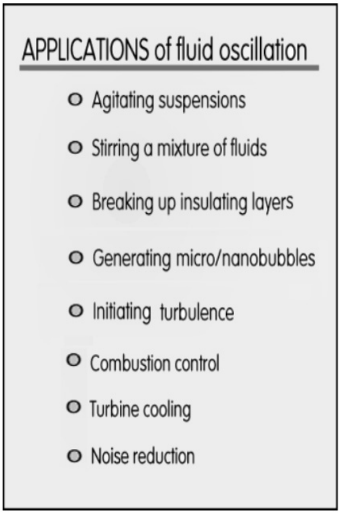


Fig. 1.1 (left) The importance of fluidic oscillators is reflected in the rapidly increasing number of scientific and engineering journal articles discussing fluidic oscillators and their uses.
Fig. 1.2 (right) A list of the most important uses of fluidic oscillators now and in the foreseeable future. Many of them are used to intensify various processes – because the pulsating flows generate more effective actions than steady flows.

The controlled handling of fluid flows has a history much older than the term 'fluidics'. Earlier devices (e.g., water wheels or compressed air control valves) were characterised by their use of mechanical moving components. With these, the devices were known as being part of the '*hydraulics*' (if the fluid was a liquid, characterised by negligible compressibility), or '*pneumatics*' (if it was a gas). The purpose of these early devices was to handle and convert the power carried by the fluid. When the idea of fluidics was introduced, it saw as its distinguishing feature not the handling of power but the processing of information in the signals carried by the fluid. Sufficient for the signal processing are very small fluid flow rates – just above the noise – so that the newly introduced fluidic devices were also made very small. This resulted in small inertial forces, making fluidic devices capable of operating at high frequencies, typically above f ~100 Hz. This value is approximately the upper limit for working with mechanical components. The high frequencies lead to fast responses, an important property for control systems.

There was a seemingly direct analogy between fluidic and electric systems in uses such as industrial automation [1.16]. The electric systems were also initially based on the moving components in relays – and later progressed to vacuum tubes in the role of no-moving-part signal amplification. Also, the early electric amplifiers were inconveniently large, delicate, and easily damaged. The working life of their vacuum tubes was so short that they had to be designed with easy replacement as one of their main aspects. Considering these obvious drawbacks of electric circuits, fluidics seemed to have a fair chance of dominating in applications such as the control of industrial manufacturing machinery. Contrary to the delicate electronics, the pure fluidic systems, when made of suitably resistant materials, can resist adverse conditions (temperature, shocks, vibration) and have very long working lives. They were demonstrated to operate reliably even when, e.g., heated to glowing white-hot temperatures or when fired from a cannon (in a flight control system for shells). In spite of these seemingly good prospects, the expectations for fluidics did not materialise. Its fate as a competitor to electronics in control systems was later completely doomed when vacuum tubes were replaced by semi-conductor amplifiers and were produced in large numbers for entertainment technology, the large production decreasing the manufacturing cost. The semi-conductor circuits could, by decimal orders of magnitude, be smaller than the devices performing the analogous task in fluidics [1.14]. Also, electronics can also operate much faster. The limit to the signal transfer velocity in fluidic circuits is the speed of sound – while, in electronics, the analogous limit is the much higher speed of light. The capability of fluidics to withstand the adverse conditions was perhaps interesting but only rarely of primary importance because the control circuits may be simply placed in some nearby location where they are not exposed to the adverse effects.

Fluidics, at that time, did not disappear completely, but was chosen for use by designers in only a few situations where some fluid had to be worked with anyway, especially if it could serve, simultaneously, as the signal carrier (e.g., used for manipulating the transport of biological samples which, simultaneously, serve as carriers of the fluidic signals). As documented in the publication rate diagram [Fig. 1.1], towards the year 2000 these uses of fluidics were more or less a rarity. The diagram shows only three or four publications appeared annually worldwide, sometimes with such extreme signal-carrying fluids like the molten metal in [1.2]. Of course, the infrequent use of the ideas of pure fluidics resulted in its being little known. There remained only a few developers interested in fluidics, mainly in power fluidics [1.17].

The change came with the seminal patent [1.18]. Its idea was to combine the process intensification effects of oscillatory flows with the advantages offered by the simplicity and low cost of pure fluidic devices. This recognition of the advantages resulted in steadily increasing numbers of applications such as those listed in Fig. 1.2. Approximately coinciding with the beginning of the new millennium, the numbers of papers published annually started to increase rapidly; this popularity is apparent from the upwards sloping line in the diagram in Fig. 1.1.

In some applications of fluidics, the fluid flow rates are varied in a continuous manner. However, many advantages are offered in fluidics using pulsed flows. Via the fluid agitation in power fluidics, the pulses lead to the intensification of various processes: thermal, chemical, or growing primitive organisms. In principle, it is a direct development from the simple stirring of tea with a spoon. The early mechano-fluidic (M/F) oscillators were typically driven by an electric motor with mechanical gears moving the stirrer, an idea development from the spoon. The mechanical components, however, are added at a considerable investment cost. In addition, of course, the economics also had to consider the running cost of driving the electricity. Many traditional M/F oscillators with mechanical acting parts also had the disadvantage of being inconveniently large and heavy. As a result, the economics of "fluidic stirring" were not favourable.

The fluidic agitation, on the other hand, with its inexpensive, no-moving-part oscillator, is typically driven by a small percentage of flow taken from the main fluid flow supplied. These aspects made a substantially favourable change in the situation from the economic point of view. In a typical heat or mass transfer process, the limiting factor to the efficiency is the boundary layer that forms on walls and acts there as a sort of insulator. The fluidic oscillator, by its agitation, breaks this layer and, thus, increases the heat or mass transport rate. This destruction of the boundary layer is a useful capability of the fluidic oscillator in such devices as, e.g., heat exchangers. Another important case among the example cases listed in Fig. 1.2 – the case to which particular attention is devoted in this monograph – is the generation of extremely small gas bubbles in liquids. This oscillator application alone, while so far not very well-known in the engineering community, has led to the development of a whole range of improvements in many areas, especially in chemical and process engineering and also in biotechnology.

1.2 Fluidic oscillatory outputs

Fluids can flow in a wide variety of flowfield configurations, depending on the geometry of the boundary conditions of the available spaces and cavities in which the flow takes place. Understanding the details and formulating the laws of these flowfields provides us with an engineering science called *fluid mechanics*. Interest in this discipline, originally, was mainly directed to flows past vehicles: airplanes and ships. These flows are the subject of studies by *external* fluid mechanics. In fluidics, the flows – governed by the same equations – take place in closed

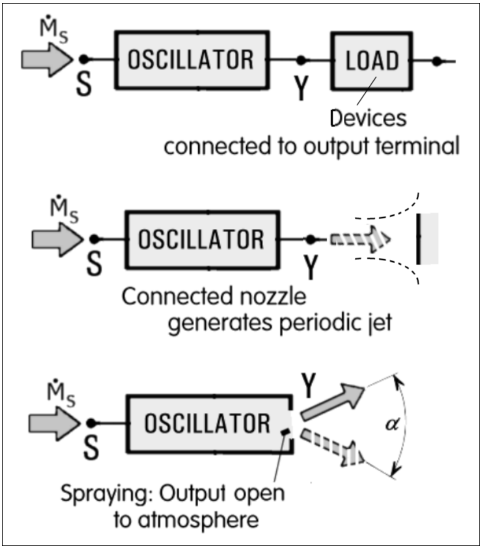


Fig. 1.3 The power outputs from a fluidic oscillator. Apart from the closed cavity power load (top) connected to the output terminal **Y**, less often, but nevertheless importantly, some oscillators (middle) have, at their output **Y**, a jet pulsating in time, (e.g., for cleaning or heating the impinging surface) or sweeping in space (bottom).

cavities so that they are a part of *internal* fluid mechanics. Because of the non-linearity of the governing equations, the solutions have to be made by numerical (rather than analytical) methods. If the flow circuit operates in an oscillatory regime, then somewhere in this chain of devices an oscillator is located. The idea of a processing chain with an output is applied less often in fluidics because the flow processing stages in the chain require a relatively large power level themselves. There are some analogies between the fluidic and electronic circuits, but this similarity should not be relied upon because there are important, non-negligible, differences. In contrast to electronics, apart from the closed cavity end stage, shown at the top of Fig. 1.3, there may be the direct outflow of a jet at the exit, having no electric analogy. In electronics, the signals are processed in a chain of miniature, extremely low-power devices, with the resultant, final output fed into a power amplifier – an electric output device.

For an output terminal in electronics, the atmosphere represents an infinitely large resistance. On the other hand, in gas fluidics the atmosphere represents the very opposite: a small (theoretically zero) resistance to the flow. If the exit flow terminal is of a large cross-section, its opening into the outer space is simply a fluid loss – while, with a small cross-sectional area it represents a useful device: a nozzle generating jet. This jet can have a useful impact on a wall positioned opposite to the nozzle exit – such as a force action, or either heating or cooling [Fig 1.3]. This may be useful with a steady flow jet. A more effective impact action is obtained by a push-pull oscillation (the middle case in Fig. 1.3, e.g., in [1.3] or [1.4]). The last case of the small section area at the bottom of Fig. 1.3 replaces the back-and-forth oscillation by sweeping spatial motions. The jet there is moving between the extreme values of the exit angle α in the plane parallel to the base plate. Also, in this case the oscillating flow is more efficient than the steady jet flow.

A special case among the uses unique to fluidic outputs are two-phase fluids with gas bubbles in the liquid, discussed later in Chapter 7. The load connected to the oscillator is, in this case, a bubble-producing aerator.

1.3 Channels for connecting devices

Fluidic devices and their terminals are mutually connected by connection channels. This has been done in classic hydraulics and pneumatics, mostly by tubes or pipes with a circular cross-section. The reason is mainly due to the, usually, higher pressure levels for which the ideal cross-section shape means only a small amount of stress on the connecting channel walls and also a minimum, overall, total weight of the circuits. In mainstream fluidics, however, the pressure levels tend to be much lower so that the round shape of the connections is less useful. More importantly, there are the aspects of the manufacturing methods. They prefer the rectangular cross-sections as shown in Fig. 1.4, made by the removal of material from one channel side wall.

The circular channel cross-section is used at the higher pressure levels in power fluidics [1.6], but even there the circular sections are less common. In fluidics, if there is a request for higher transferred power, preference is usually given to increasing the flow rates rather than to applying high pressure levels. The main decision factor in the shape of the connecting channel is their manufacturing method. In fluidics, the round cross-section tubes are often used in bench tests of fluidic laboratory models. There, it is usual to have exchangeable connections by the use of deformable tubing of a soft polymeric material. The assembling and disassembling of the circuit in these test runs is obtained without any tool, simply by pulling the soft tube end over a short ferrule (a stub pipe) located at the device terminals.

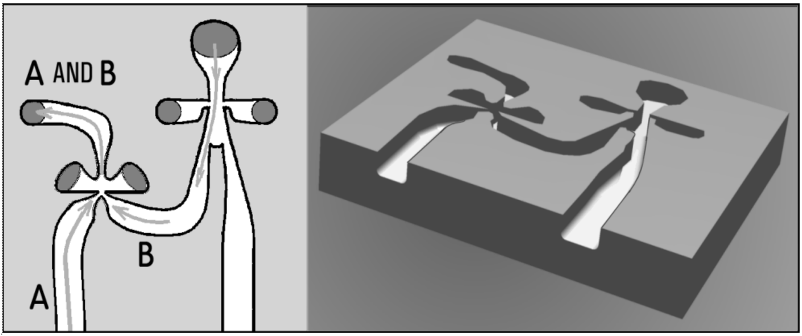


Fig. 1.4 Example of an extremely simple fluidic integral circuit consisting of only two devices, mutually connected by the flat, rectangular cross-section channel **B**. Both the devices and the connecting channels are made by the removal of material from the base.

Later on, when the behaviour of the circuit is proven to be satisfactory, the devices are connected by the permanent channels made via the removal of material from the plates such as, e.g., photoetching. As shown in Fig. 1.4, the permanent configurations are suitable for manufacturing simultaneously with all circuit components. The flow inside the permanent connecting channel takes place between the top and bottom surfaces (the top cover plate is not shown in Fig. 1.4). At the constant depth of the cavities, the local flow velocity is inversely proportional to the local cavity width. A very simple example of a fluidic integral circuit (Fig. 1.4), consisting of only two devices (a switched amplifier and a logic device **AND**) mutually connected via channel B of the rectangular cross-section. The cavities are made by the removal of material from the base plate –

such as by laser cutting, photoetching, photolithography or similar processes, with the cavity contours transferred photographically or by a computer programme with a 3D printing facility. The **AND** device performs a logical operation: it generates an output flow signal if, and only if, there are input flows present in both inlets, **A** as well as **B**. Not shown in Fig. 1.4 are the four terminals with fluid flowing out of the circuit plane in a perpendicular direction. They lead to the ferrules (not seen in this illustration), while the four vents (there are two in the **AND** device, as well as two in the amplifier) are simply open to the atmosphere or to a large settling chamber.

1.4 The basic parameter: fluid mass flow rate $\dot{M}$

In Fig. 1.5, the definition of the fluid flow magnitude in a typical fluidic connecting channel with a rectangular cross-section is shown. The flow is oriented perpendicularly to the plane of the cross-section area, bh. This magnitude of the fluid mass flow rate $\dot{M}$**,** is the parameter of utmost importance in the design of fluidic circuits. Instead of the $\dot{M}$**,** sometimes different related parameters are used. They may be more convenient but

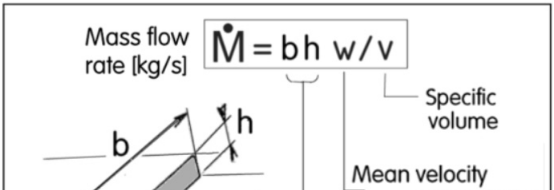


Fig. 1.5 The mass flow rate in a channel of a flat, rectangular cross-section. The actual distribution of velocity w in the section plane is often much more complex – but for the approximate mass flow rate calculations, the mean velocity value is used more often.

are less justified from the basic fluid mechanics point of view. For the mass, a universal conservation loss is valid. A typical example of such an alternative parameter is the volume flow rate for which the conservation law is only approximate. It may seem to be a good choice because it is the very quantity that is often displayed as their output variable by many flow-meters used in experimental fluid mechanics. The problem with the volume flow rate – especially in the flows of a gas – is caused by fluid compressibility. As an identical amount of fluid is transported through the channel per unit of time, the compression causes the numerical value of the volume flow to vary undesirably with the local pressure [1.1]. If the fluid is a liquid of small compressibility – or the pressure changes in the circuit are small – these compressibility effects may be ignored. Nevertheless, they may sometimes cause serious complications and it is advisable to use the mass flow rate everywhere because mass is a quantity for which a mass flow rate applies, the evaluation of which needs a re-calculation from the flowmeter data. The mass conservation law ensures that the sum of the mass flow rate input into a device at **X** at each instance of time always equals the sum of the mass flow rate output at **Y** – perhaps decreased by the fluid mass stored temporarily inside the device. Because of the invariance of the mass flow rate (independence from the pressure and other parameters, such as temperature), it is easy to formulate the conservation law as

$$\sum_{i} \dot{M}_{Yi} = \sum_{s} \dot{M}_{Xs} - \dot{M}_{V} - dM_{accu}/dt \qquad \ldots (1.1)$$

The law eq. (1.1) is formulated more generally here than is needed for most calculation tasks in fluidics. The form shown here is valid for a device with *i* inlets, *s* outlet terminals and also for the accumulation (defined in the last term of the equation). The flows in eq. (1.1) also take into consideration the flow rate through the vent $\dot{M}_V$ if the device possesses one. The vent **V** is an exit from the device that has an auxiliary role of providing a path out from the device for the fluid if the output terminals are more, or less, blocked by the connected high-resistance loads.

1.5 Definition of an oscillator

Fig. 1.6 shows a schematic presentation of a simple two-terminal fluidic oscillator. It is supplied with a constant input fluid flow from an external source into its input inlet **X**, which may (in this case) also be seen as the supply terminal **S**. In response, it produces a periodic flow in the output terminal **Y** which may be approximated by two extreme cases, presented in Figs. 1.7 and 1.8. One approximation, in Fig. 1.7, consists of a series of flow pulses with both inlet and outlet sharp edges (generated by

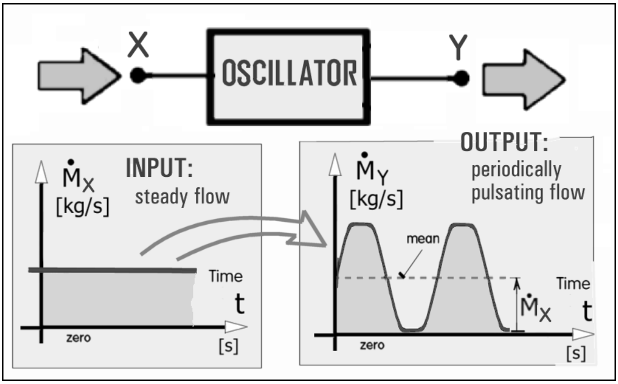


Fig. 1.6 The purpose of an oscillator is to convert the steady flow rate $\dot{M}$ delivered to the input **X** into a periodically varied flow at the output **Y**.

extremely fast flow switching). The other extreme, Fig. 1.8, is a harmonic, continuous tone signal. The mass conservation equation for the flows into and out of these approximation cases in Fig. 1.6 is the eq. (1.2). It is a simplified version of eq. (1.1) for the oscillator configuration with no vent, only one inlet terminal **X** (also having the role of the supply terminal **S**), and a single outlet **Y**.

$$\dot{M}_Y = \dot{M}_X - dM_{accu}/dt \quad \ldots (1.2)$$

The diagrams of the time dependences of the mass flow rate in the terminals **X** and **Y** are presented in the bottom part of Fig. 1.6. They describe the behaviour of fluidic oscillators as the devices convert the steady input flow into the periodically varied output flow. It should be noted that, because of the instantaneous differences between the flows in **X** and **Y**, it is necessary to have the last term of eq. (1.1) in eq. (1.2). This is needed to describe the instantaneous temporary accumulation of fluid somewhere inside the oscillator device.

An alternative to this internal storage are oscillators with an auxiliary vent terminal **V** into which (or out from which) flows the instantaneous fluid flow difference between the flows between terminals **X** and **Y**. As discussed in other chapters of this monograph, in particular in Chapter 4, there are many alternative variant oscillator design configurations [1.7] with several terminals. These configurations differ in their various aspects – apart from the number of terminals, the most important difference is in the

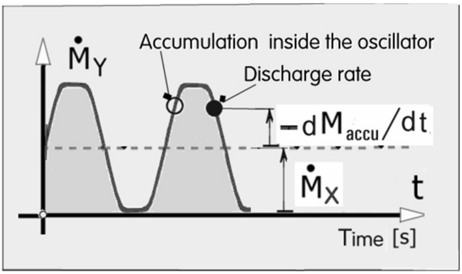


Fig. 1.7 During an oscillation cycle, some fluid has to be temporarily accumulated over a part of the cycle and then in the remaining time discharged to the output terminal.

character of the pulsating or alternating output flows generated. Another often encountered oscillator output is the superposition of the oscillation and the steady component. In Fig. 1.8, four examples are presented. They all belong to the oscillator family with the output flow of a harmonic character – which means the output flow signal has, in this case, only a single component in its frequency spectrum. The four cases in Fig. 1.8 are oscillations with various relative magnitudes of the superposed steady component. The named examples presented there cover the range from the small pulsation magnitude (**a**) to the fully alternating (**d**). They may be the result of the presence of some rectification phenomenon in the oscillator – an effect with practical use in synthetic jet devices [1.8], [1.9] – or the result of a steady flow admitted for some purpose in the applications (e.g., to avoid overheating and steam generation with locally generated heat if the heat absorbing fluid is not exchanged by the steady component for a cold one).

In an analogy to an earlier development that took place in the history of electronics, in fluidic circuits now, there is a general trend to handle the information encoded into pulses – in the simplest case coded into the number of individual flow pulses counted while they pass through a certain terminal during a given period of time. In Fig. 1.9, idealised rectangular pulses are shown. The main advantage of encoding into the pulses is the resultant much higher resistance to distortions inevitably present in the flow through the channels connecting the devices in the wave-train – if for no other reason than because of the turbulent character of the typically generated output flows in fluidics. The actual shapes of the produced pulses may be the result of contributions to their spectrum from the various resonance frequencies added. As a result of these additional contributions to the fundamental spectral component [Fig. 1.10], the diagrams of the time dependences of the pulse flow are variously deformed. Because of the time shifts between the different individual pulse periods, the results are that the various shape deformations differ between neighbouring pulses. Moreover, the pulse shape deformations caused by the turbulence are of a chaotic character. The frequency spectrum of the rectangular pulses' wave-train presented in Fig. 1.10 receives, due to the signal deformation, additional spectral components. These local spectrum deformations are not important in the pulse encoding because what matters there is the number of pulses and not their shape, however deformed they may become.

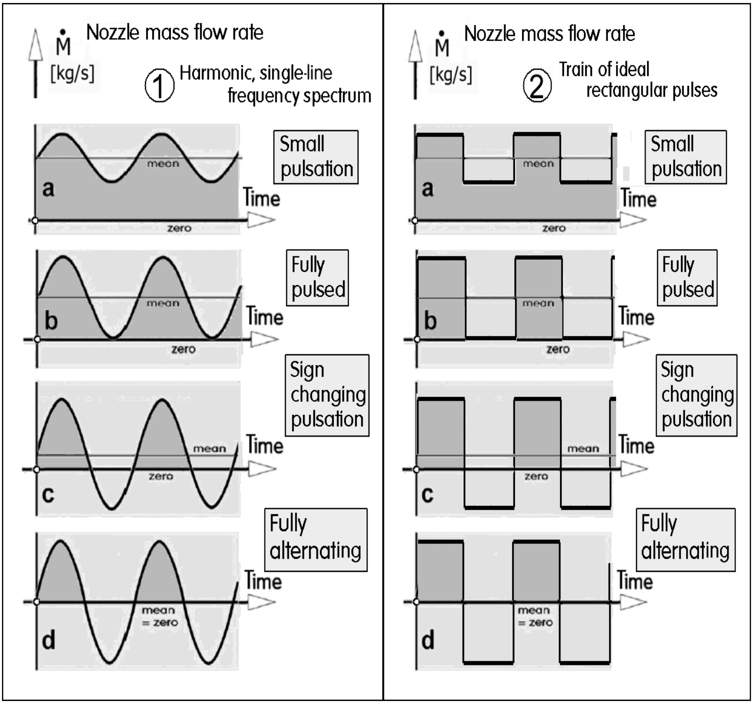


Fig. 1.8 (left) Time dependences of harmonically (sinusoidally) oscillating fluid flows with various relative magnitudes of superposed time-mean components.
Fig. 1.9 (right) Time dependences of flows switched between two stable states, especially the fully pulsed case '**b**' which, nowadays, has been increasing in importance – also due, among other reasons, to its easy realisation in bistable valves.

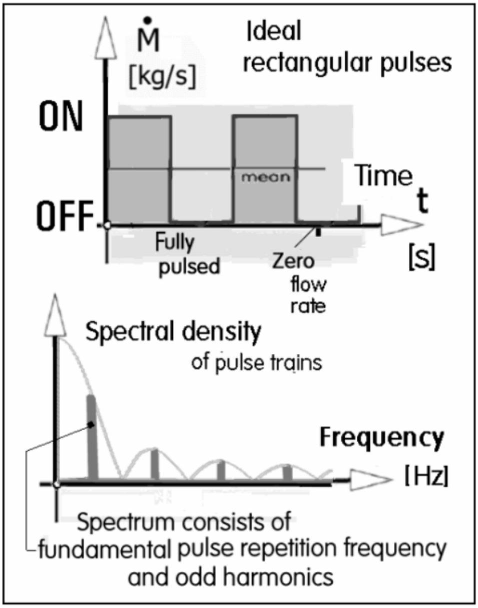


Fig. 1.10 The ON-OFF periodic flow alternating between two states generates a train of pulses. The real shapes of the pulses are usually more complex than the rectangles shown here. They contribute to the spectrum by added parasitic resonances.

1.6 Mechanisms of fluid oscillation

There are four conditions that have to be satisfied by a fluidic device if it is to be suitable for use as an oscillator generating periodic oscillation. They are listed in Fig. 1.11 and are valid universally, not only in fluidic devices for which they are formulated here.

The first condition is the requirement for the existence of an ***equilibrium*** state in the device behaviour. This is the state in which all the forces acting on the fluid in the device are mutually cancelled. As a result, the fluid can remain stationary for an unlimited time in this state.

The second condition in Fig. 1.11 is the requirement for the ***stability*** of this equilibrium. The ***stable*** flow inside a fluidic device turns back when disturbed by the fluid flow being pushed slightly away from the equilibrium state.

Then, there is the third requirement in the list. It is the existence of a significant ***inertia*** in the fluid [Fig. 1.11]. Due to the presence of this property, the fluid continues its return flow in the direction towards the equilibrium state. It moves in this direction even though the equilibrium has already been reached – and even crossed so that the fluid flows back past it. Thus, the returning fluid flow reaches the unsteady states located on the opposite side from the original return towards the equilibrium. Obviously, the directions are then reversed. Thus, these periodically reversed flows cause at least some of the repeated ***overswinging*** of the fluid into the regime. It is this periodic repetition that results in the desirable oscillation motions.

The fluid flow is driven by forces which – at least for some of them – decrease in intensity with the increased distance from the equilibrium state. At least, this is the most important case of dissipative forces. The consequence of this is fluid flow ***damping.***

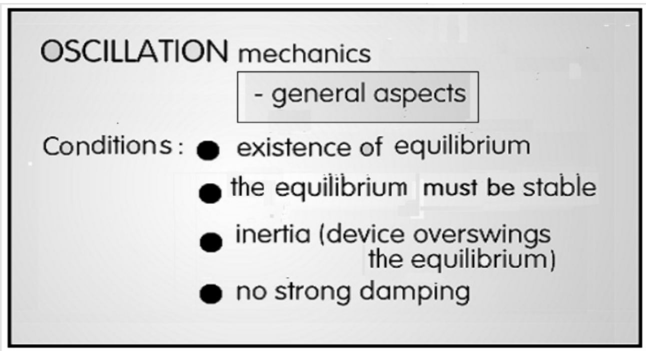


Fig. 1.11 Generating the oscillation requires meeting the conditions listed in this box.

There are three possibilities of the overswing phenomena as follows:

a) If the damping force, relative to the overswing driving forces, is weak the amplitude of oscillation gradually increases with each of the performed oscillation cycles. In this case, the oscillation amplitude grows and finally reaches the level at which something in the system collapses.

b) If the damping is relatively strong, the fluid flow rate performs a more or less non-periodic trajectory in the state space, perhaps with a few recognisable initial cycles. It is usually quite useless from the point of view of oscillator design.

c) Between the two extreme cases a) and b) may be found the periodic regime in which the amplitude, after a certain initial adjustmenttime segment, is kept constant. This is the proper oscillator behaviour. Its finer details of a desirable amplitude and deviation from pure harmonic pulse shapes (deviating due to the non-linearity) may be adjusted by varying the intensity of the damping.

1.7 Size scales of fluidic devices

1.7.1 Mainstream fluidics

Historically, when the, then, new no-moving-part pure fluidic devices were added to the repertoire of tools for manipulating fluid flows for the first time, the interest in control systems at that time was directed to processing information. Therefore, the earliest fluidic devices were developed for handling signals. For this purpose – signal amplification and

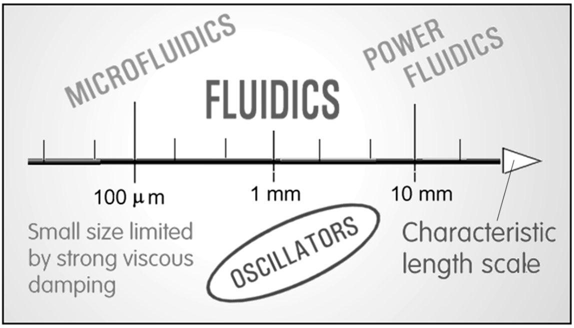


Fig. 1.12 The size spectrum of the characteristic dimensions of present-day fluidic oscillators. There are now three development trends: apart from mainstream fluidics there is a trend towards the small scale of microfluidics [1.1] and, on the other side, there is power fluidics which is characterised by the large scale.

Boolean operations – the devices were of a small size of the order of millimetres. There were expectations for the future of fluidic integral circuits. After the failure in the competition with electronics came a period of the neglect of fluidics. The revival came with a different application – on process intensification. This has remained the main subject of the development of fluidics up to today. A common standard has been fluidic devices in less complex applications, with only a few devices – such as just a fluidic oscillator. These devices had to be somewhat larger and work at a higher Reynolds (Re) number. The size scale of their absolute dimensions became as indicated in the middle of the fluidics range in Fig 1.12. The working principle is mostly the idea of deflecting a submerged jet captured in a collector. The characteristic dimension for the evaluation of a Re number is the width **b** of the jet-generating nozzle. The typical scale of mainstream fluidic devices as they are today, in laboratories interested in fluid mechanics, is only small multiples of 1 mm. The range is from the smallest nozzle widths at **b** ~ 0.3 mm to the largest **b** ~ 30 mm. The corresponding overall size of a fluidic amplifier as a typical fluidic device is between ~ 50 mm and ~ 150 mm. This is a convenient size to work with in a fluid mechanics laboratory.

1.7.2 Microfluidics

An important current development trend, to a certain degree made possible by the development of methods of manufacturing very small objects, is ***microfluidics*** [1.1], [1.10]. Its advantages are listed in Fig. 1.14. Typically, the standard became a sub-millimetre size scale, while mainstream fluidics functioning relies on fluid dynamic effects; the, characteristically, very small Re number flows in microfluidics are dominated by viscous forces. To avoid poor performance, there has been recent interest in various uncommon mechanisms, such as electrically driven viscosity. For the manufacture of, typically, very small devices, methods taken over from microelectronics may be used, such as photolithography. Also, additive fabrication methods are often applied now – the so called 3D printing [1.13]. This process involves melting a small amount of the device material into a droplet, which is accelerated towards the produced object onto which the droplet attaches and solidifies at the desired location of the manufactured object. Among other aspects, the advantage of miniature microfluidic devices is their portability. The devices have already been successfully implanted subcutaneously into a living creature, an animal or even a human body, with minimal inconvenience, e.g., for microfluidic blood pressure control. The microdevices also possess an advantageous ratio of the surface to the volume so that, for example, when used in the role of miniature chemical microreactors, they are fast heated as well as fast cooled. This fast change results in the close temperature control of the conditions in the reactor. Also, because of their small size, the devices may be economically produced from very expensive or rare materials and can also handle dangerous

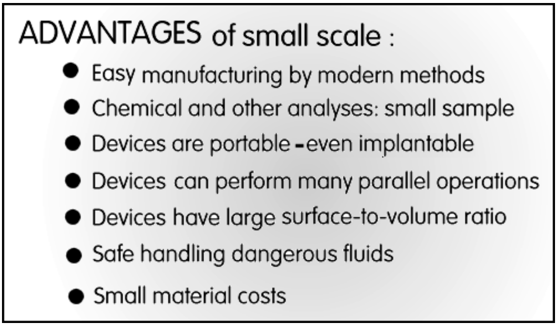


Fig. 1.14 Microfluidics bring a number of advantages – unless, of course, there is a demand for a large output mass flow rate or high power [1.1].

fluid samples (e.g., explosives) quite safely. Even when processing a harmless material, the collecting of small fluid samples is associated with the least inconvenience or influencing of the investigated object.

The difficulty encountered in microfluidics is the problem of a small Re number – the ratio of the characteristic dimension b multiplied by the flow velocities and divided by the fluid viscosity. At the low Re values, the viscous damping may be dominant. There are pressure-driven microfluidic devices that can use the operating principles of the large-scale devices [1.1], but when the Re values are really small, it becomes necessary to introduce principles that are different from fluid dynamics.

1.7.3 Power fluidics

The opposite development trend, away from mainstream fluidics, is ***power fluidics*** [1.1], [1.16]. Its characteristic aspect is the large size of the devices. This is in accordance with the typical trend of fluidics: reaching the requested large power levels by large fluid flows – and not by high pressures. In principle, the large total flow may be obtained by operating a larger number of devices in parallel – but this is not universally applicable and may not be the best choice from the point of view of the economics.

The typical power levels dissipated in the jets issuing from the nozzles have been of the decimal orders of magnitude from 1 W to 100 W. The corresponding overall size of a typical fluidic amplifier is between ~ 50 mm and ~ 150 mm.

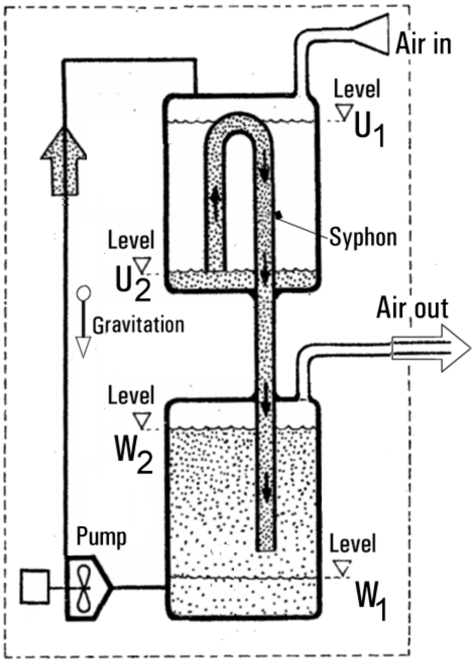


Fig. 1.15 An example of an unusual no-moving-part oscillator typical in power fluidics. It generates short air flow pulses at an extremely low frequency (of the order up to hours).

Apart from the two, already classic, amplifier and oscillator jet-deflection principles, power fluidics came with several extraordinary versions.

One of them, an oscillator based on the relaxation principle, is presented in Fig. 1.15. It is an airflow oscillator performing an operation with conversion into the gravitation energy of a liquid. For a simplification of the presentation, this oscillator is drawn as driven by the pump circulating a constant amount of the liquid. There are two alternately filled vessels, vertically arranged and connected by a syphon tube. The pump slowly fills the upper vessel as well as the bottom part of the syphon with water. When the rising liquid surface reaches the level U_1, the water is suddenly rapidly discharged through the syphon into the bottom vessel, displacing the air from it, which is then delivered into the oscillator output terminal. This air flow pulse ends when the water in the syphon decreases to the level U_2 and the syphon fills with the air.

1.8 Mechano/fluidic devices as the starting point

Even though many advantages are obtained from pure fluidics thanks to the absence of moving mechanical components, there are cases in which the conditions are different. The solution of a given fluid flow problem may be, in some aspects, better if the designer accepts the version with a mechanical motion. Contrary to the earlier large-scale mechanical designs, similar for example to Fig. 1.16, recent versions are often influenced by small-scale fluidics as made by the newer fabrication methods recently brought by the pure, no-moving-part fluidics. One of the advantages of movable mechanical components is easily understanding their operation. In pure air flow fluidics with transparent bodies, there is no visible indication of the instantaneous state – while in devices similar to Fig. 1.16, the states and their changes are visible from the piston position. Of course, the M/F is slow and one has to also be prepared for the worst enemy of mechanical components, the never completely eradicated possibility of the movable component getting stuck (perhaps because of accumulated dirt).

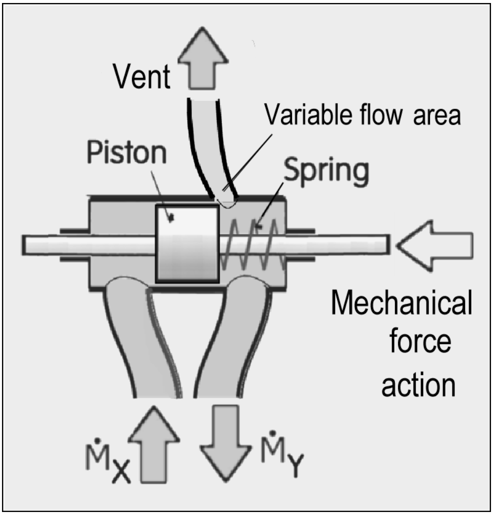


Fig. 1.16 A simplified presentation of typical large-size mechanical flow control components used in power fluidics. The mechanical parts complicate fabrication (they need the assembly of the components) and are vulnerable: the piston may seize and the spring may break due to material fatigue.

If the M/F device operates by component elastic deformation instead of translations, the function of a spring or membrane may be suddenly stopped by material fatigue. A very important variant of the mechano/fluidic devices for flow control are sliding valves which vary the available fluid flow area, examples of which are shown in Figs. 1.16, 1.17, and 1.18. They control the fluid flow rate by varying the available cross-section area for the flow. It should be noted that the mechano/fluidic valve may operate up to its extreme regime of a full flow stop – something absolutely impossible to reach in pure fluidics.

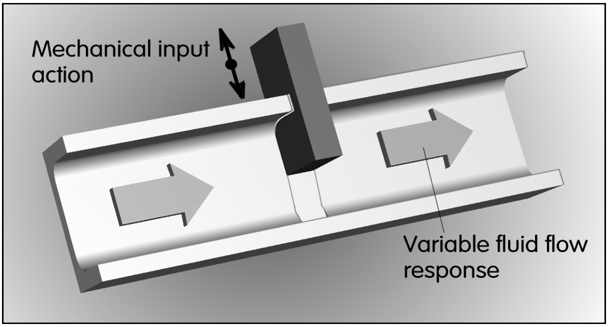


Fig. 1.17 Turning down the fluid flow mechanically by the transversal slider which more or less obstructs the available cross-section area in a channel.

A typical turn-down valve with a slider is presented in the left-hand area of Fig. 1.18. There is quite a large orifice for the main flow passing through it if there is no control action in **X** and the slider is, as it is in Fig. 1.18, in its OPEN position, causing a minimum or practically zero resistance to the flow. The higher the slider is in its movement upwards in Fig. 1.18, by the input in **X** towards the CLOSED state, the smaller the section of the orifice is which remains available for the fluid flow. In the top slider position in Fig. 1.18, the flowpath is completely blocked. In many applications, the source for the fluid supply **S** is a pump. There are types of pumps used as fluid flow sources for fluidics that cannot accept the full closing of their supply terminal **S** (or of the output terminal **Y**). Such pumps respond to this slider flow closure by stalling, or otherwise stopping it from operating properly.

This problem of the turn-down valves is solved by the diverter valve version shown schematically on the right-hand side of Fig. 1.18. The fluid that cannot get into the **Y** trough via the blocked orifice has an opportunity here to leave harmlessly through the available vent **V**. This diverter principle is very common in no-moving-part fluidics where it is seen as a composition of two turn-down valves operating anti-parallel – opening one coincides with closing the other.

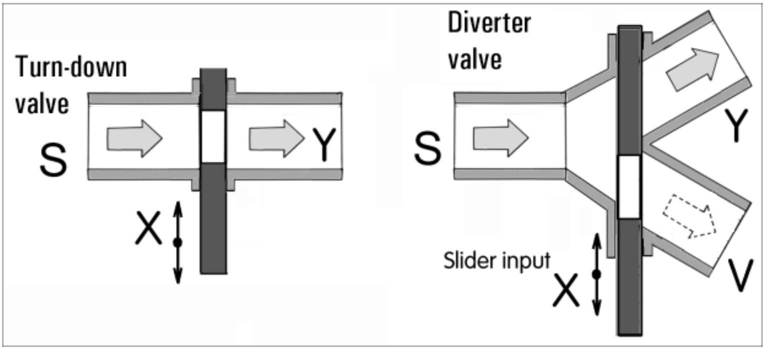


Fig. 1.18 Two basic principles of fluid flow control by a mechanical valve (a slider as in Fig. 1.17). The flow into the output terminal **Y** may be varied either by obstructing the cross-section area (at left) or by diverting the fluid into the vent outlet **V** (right-hand side of the picture).

References

[1.1] Tesař, V. '*Pressure-Driven Microfluidics*', Monograph, Artech House Publishers, MA 02062 USA, July 2007

[1.2] Tesař, V. '*Fluidic control of molten metal flow*' Acta Polytechnica, Vol. 45, p. 15, 2003.

[1.3] Nishri, B. and Wygnanski, L., '*Effects of periodic excitation on turbulent flow separation from a flap*' AIAA Journal, Vol. 36, p. 547, 1998.

[1.4] Bons, J. P., Sondergaard, R. and Rivir, R. B. '*The fluid dynamics of LPT blade separation control using pulsed jets*' , Journal of Turbomachinery, Vol. 124, p.77, 2002

[1.5] Gilmour, D.J. and Zimmerman, W.B. '*Microbubble intensification of bioprocessing',* Chapter in Advances in Microbial Physiology, Elsevier, 2020

[1.6] Tesař, V. '*A mosaic of experiences and results from development of high-performance bistable flow control elements*', Proceedings of the Conference 'Process Control by Power Fluidics', Sheffield, United Kingdom, 1975

[1.7] Tesař, V. "*Taxonomic trees of fluidic oscillators*", European Physics Journal Web of Conferences, Vol. 143, Article No. 02128, 2017.
[1.8] Tesař, V., Hung, C. H. and Zimmerman, W. B. '*No-moving-part hybrid-synthetic jet actuator'*, Sensors and Actuators A., Vol. 125, p. 159, 2006.
[1.9] Tesař, V. and Kordík, J. '*Quasi-similarity model of synthetic jets*'. Sensors and Actuators A: Physical, Vol. 149, p. 255, 2009.
[1.10] Tesař, V. "*Fluidic circuits*", Chapter in Microfluidics: History, Theory, and Applications', CISM courses and lectures No. 466, Springer Wien, New York, 2006.
[1.11] Lin, J. C., et al. '*Full-scale testing of active flow control applied to a vertical tail*', Published online: 8 Feb 2019 ARC https://doi.org/10.2514/1.C034907
[1.12] Kolodjski, K. J.'*Constant temperature anemometer*' Patent US4503706 Filed May 1983.
[1.13] Tesař, V. and Šonský, J. '*Fluid mechanics of molten metal droplets in additive manufacturing*', International Journal of Computational Methods and Experimental Measurements, Vol. 4, p. 403, 2016.
[1.15] Foster, K. and Parker, G. '*Fluidics – components and systems'* Wiley-Interscience., 1970.
[1.16] Belsterling, C. A., '*Fluidic systems design'* Wiley-Interscience, 1971.
[1.17] Priestman, G. H. and Tippetts, J. R. '*Development and potential of power fluidics for process flow contro*l' Chemical Engineering Research and Design, Vol. 62, p. 67, 1984.
[1.18] Zimmerman, W. and Tesař, V. '*Bubble generation for aeration and other purposes*'. Patent GB 0 621 561.0, Filed Oct. 2006.

CHAPTER 2

FLOWS IN FLUIDIC DEVICES

2.1 Fluidic flowfields

There are a wide range of alternatives for fluid flows in the internal cavities of fluidic devices, from a simple constant-width channel to a complex of mutually interacting internal flows entering into the cavity from several inlets. Corresponding to the behavioural complexity are the complex geometries of the cavities in which the flows take place. Added to the problems of spatial flow complexity in fluidics is the problem of their unsteadiness – an inevitable aspect of oscillators, which are the main subject discussed here. Solutions to the flowfields are difficult because they are governed by the non-linear, partial differential equations of fluid mechanics. They cannot be solved in a closed analytical form but have to rely on the finite-element numerical approaches that can be made very fine by dividing the flowfield into a large number of very small elements. This, of course, makes the computations extremely time-demanding. Moreover, the flows in fluidics are mostly of a turbulent character (laminar flows do exist in fluidics, but are exceptional) so that there are additional difficulties caused by the lack of an exact theory of turbulence. Software for these numerical solutions are available commercially, but have the character of an almost separate field of science, require a quite extensive amount of knowledge, and are also financially demanding. Even on a very powerful computer system, the solution may take a long time. It is particularly expensive in the already mentioned problem of the unsteadiness in fluidic oscillators, where the run up to the final convergence has to be repeated many times at each of the many instants in the oscillation cycle.

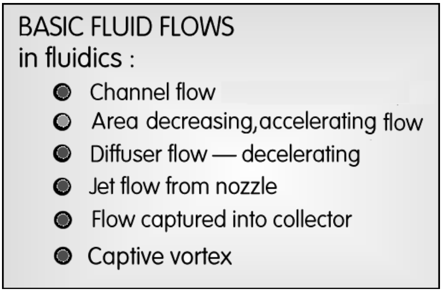


Fig. 2.1. The main flowfield configurations in fluidic devices, studied as a specific part of fluid mechanics. This list shows the particularly important cases of flows encountered in fluidics.

As a result, most investigations of fluid flowfields in fluidics rely on experiments. It is, itself, also an extensive subject, requiring expensive electronic instrumentation for pressure and anemometry measurements. What is helpful in this difficult situation is the existence of qualitatively, more or less, similar flowfield solutions, accumulated from the studies of various fluidic device components. It can help in the understanding of various typical aspects, evaluated and stored for later use in similar cases. Among the already existing solutions, the six basic flowfields listed in Fig. 2.1 are typical. Of particular importance for fluidics is the case of the submerged jets, formed by issuing from a nozzle into a larger downstream space. The adjective '*submerged*' when applied to them means the space into which the jet flow is filled by the same fluid as that of the studied jet. Another important case, the decelerating diffuser flow, is often located downstream from a collector capturing the jet flow. In fluidics, the flows which have the character of captive vortices are of a different character. They rotate inside a closed cavity (usually of cylindrical shape), with a central outflow and the rotation driven by a tangential inflow at the circumference.

2.2 Simple flows: a one-dimensional approach

Fluid flows in the cavities of fluidic devices dissipate the energy of the organised motions (flows), converting them into the chaotic, unorganised energy of thermal motions by internal friction. In a flowing fluid, there are two main components of the energy: **(a)** specific kinetic energy $\mathbf{e}_{\mathbf{kin}}$ and **(b)** specific pressure energy $\mathbf{e}_{\mathbf{press}}$. The former is characterised by the magnitude of velocity w [m/s] of the fluid motion – while the latter is characterised