Synthetic Jet Cooling Part I: Overview of Heat Transfer and Acoustics

Clemens J.M. Lasance[1], Ronald M. Aarts[1,2]
[1]Philips Research Laboratories, [2]Eindhoven University of Technology
High Tech Campus 4, 5656 AE Eindhoven, The Netherlands
clemens.lasance@philips.com

Abstract

The paper deals with an overview of the principles of heat transfer and acoustics related to a promising alternative for fans: synthetic jet cooling. After a short discussion of the benefits, the background and the principles underlying the physics are treated. The problems with optimisation through numerical analysis are highlighted. An accompanying paper discusses the experimental results in terms of heat transfer and noise for a special embodiment: an acoustic dipole cooler.

1. Introduction

Many current and future consumer products suffer from thermal problems due on the one hand to miniaturisation and more features leading to increased temperatures, while on the other hand the customer expects higher reliability and less noise. Natural or forced cooling with air will be the preferred choice for a long time to come for many consumer products with the exception of computers. Unfortunately, the cooling potential of natural convection is reaching its physical limits in today's products. However, there is a certain reluctance to switch to fans due to the disadvantages usually associated with them. A cooling technology that could significantly enhance natural convection while at the same time relaxing many of the drawbacks of a fan would be an interesting option for many electronic products. One of the most promising options is to use jets, in particular synthetic jets. Basically, the technology requires only a small loudspeaker and some electronics.

The benefits are somewhat dependent on the application, but in general the following improvements are expected when comparing synthetic jet cooling with fans, for the same heat transfer performance:

- (much) lower noise level
- better (thermodynamic) efficiency, half the power or less
- design-friendly because of much better form factor
- intrinsic higher reliability
- less fouling problems, the vibrating part can be protected from the ambient
- miniaturisation easier than with fans
- relatively simple noise cancellation possible

2. Physical principles of synthetic jets

It is well known that a jet generates sound, conversely the opposite is also true: sound can generate jets. This phenomenon is known as acoustic streaming. Acoustic streaming is essentially a net mean flow generated by a sound field. Basically, the sound wave is attenuated by the viscosity and the inertia of the medium, resulting in a pressure gradient along the wave propagation direction exerting a body force on the medium leading to induced flow. Faraday, in 1831, was the first to describe empirically the flow that develops near a vibrating surface. Just over 100 years ago, Rayleigh was the first to provide a theoretical description that is still valid today to a first approximation. From a theoretical point of view a major problem is that acoustic streaming is driven by non-linear effects and hence cannot be analysed using linear acoustics. Noteworthy are the various classifications in literature, all with their own simplifications of the full Navier-Stokes equations: boundary-layer-driven streaming, outer streaming, inner streaming, Rayleigh streaming, Eckert streaming, Stuart streaming, Gedeon streaming, jet-driven streaming, travelling-wave streaming, small-scale or large-scale streaming, slow or fast streaming. This is one of the reasons that the phenomenon is difficult to understand. One of the results is that it is rather complicated to explain the physics to people who are not experts in fluid dynamics. Two overviews have been published: by Lighthill in 1978[1], and by Boluriaan and Morris in 2003[2].

One of the most important applications that motivated research in this field is the use of acoustic streaming for aerodynamic flow control devices resulting in drag reduction, lift enhancement, mixing augmentation and flow-induced noise suppression. The interaction of synthetic jets with an external cross flow over the surface in which they are mounted can effect flow changes on length scales that are one to two orders of magnitude larger than the characteristic scale of the jets. A review covering this application field has been published by Glezer and Amitay in 2002[3]. Some other applications are: propulsion, micropumps, non-contact surface cleaning and heat transfer enhancement. Focusing on cooling, already in the late 1930's Marthelli and Boelter[4] reported enhancement over natural convection from a vibrating horizontal cylinder. Vainshtein et al,[5] analysed the heat transfer between two plates at different temperatures and showed that the heat transfer could be enhanced by an order of magnitude using high-frequency, high-amplitude sound fields.

Contrary to a traditional jet, a synthetic jet operates without net mass injection and is constructed from the surrounding fluid, see Figure 1.

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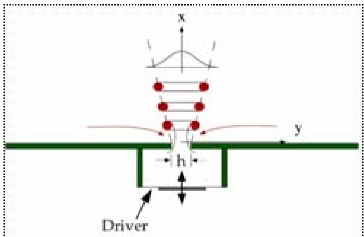

Figure 1: Sketch of synthetic jet formed by an actuator in a cavity provided with an orifice [10]

In more technical terms, it is a device that requires zero mass input yet produces non-zero momentum output. They are synthesized from the coalescence of a train of vortices as a result of a time-harmonic motion of a diaphragm driven by whatever means, piezoelectric, mechanical or magnetic, provided the amplitude is large enough to induce flow separation at the orifice. In this case a shear layer is formed between the expelled fluid and the surrounding fluid. This layer of vorticity rolls up to form a vortex ring (axisymmetric) or vortex pair (two-dimensional slot). A synthetic jet is nothing more than a sequence of vortex rings created one after another. Without the time-harmonic motion, the phenomenon of vortex ring creation is actually a well-known daily occurrence, many people have tried at one point or another to blow smoke rings. A design known as a smoke-vortex launcher is very popular in undergraduate physics demonstrations, see Figure 2.

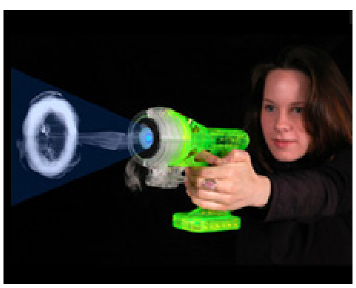

Figure 2: Typical vortex launcher

Jet formation associated with oscillating solid boundaries have been the subject of numerous investigations. As early as 1950 Ingard and Labate[6] used standing waves in an acoustically driven circular tube to induce an oscillating velocity field of an orifice plate placed near a pressure node and observed the formation of jets from trains of vortex rings on both sides of the orifice. In 1975, Mednikov and Novitskii[7] reported jet formation without net mass flux and average velocities up to 17 m/s by inducing a low-frequency velocity field with a mechanical piston. In 1980, Lebedeva[8]created a round jet with velocities up to 10 m/s by transmitting high amplitude sound waves through an orifice placed at the end of a tube. A major contribution to the theory and application of synthetic jets has been realised by Glezer's group at Georgia Tech in Atlanta. The first paper on synthetic jet cooling appeared in 1997[9]. Smith and Glezer[1]presented a useful overview of the formation and evolution of synthetic jets focusing on a plane two-dimensional jet formed by the motion of a circular diaphragm driven at resonance (nominally 1140 Hz) in a sealed cavity with a rectangular orifice measuring 0.5*75 mm. One of the observed differences with conventional 2D jets is that the net entrained volume flow rate is substantially larger. Smith and Swift[11] showed the difference between steady and oscillatory flow losses caused by bends, expansion and entrance effects, mainly for understanding the acoustic streaming losses for thermo-acoustic engines. The interaction of adjacent synthetic jets has been studied by Smith and Glezer[12]. Recent papers covering practical applications are [13, 14, 15, 16, 17, 18, 19, 20, 21, 22].

3. Synthetic jet design: acoustic considerations

The investigation of reproduction of low frequency sound signals by means of small transducers with an acceptable efficiency has recently led to resonant loudspeaker systems[23]. These systems consist of a loudspeaker connected to a tube that acts as a resonator. In the optimal condition the pipe length must be of the order of λ/4, with λ the acoustical wavelength. It was observed that the sound waves produced by these systems generate pulsating air streams near the outlet of the tube. Ideally we want to use a small loudspeaker with large amplitude to generate the jet. Small cabinet loudspeakers are quite inefficient. Fortunately we are not concerned with achieving a flat Sound Pressure Level (SPL) response and therefore we can provide a system with greater usable efficiency. Such a non-flat design can be constructed with a very compact housing[24, 25], but small drivers usually require a relatively large cone excursion to obtain a high SPL. In[23] a new solution is presented that uses a resonant combination of a coupling volume and a long pipe-shaped port. The efficient resonant coupling of the driver to the acoustic load by this construct enables small drivers with modest cone displacement to achieve a high SPL.

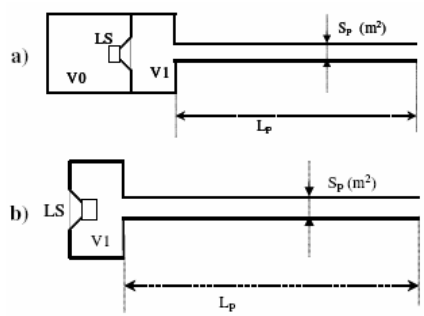

Figure 3: Schematic construction of loudspeakers. (a) Band-pass enclosure with long port. (b) Bass-reflex enclosure with long port

We define the frequency f_0 for the configuration of Figure 3a as the resonance frequency of the box with closed volume V_0 plus the driver, in the absence of volume V_1 and the pipe. In the case of Figure 3b $f_0 = f_b$, where f_b is the free air resonance frequency of the driver. With a band-pass box design, f_0 usually coincides with the Helmholtz frequency f_H. However, for long pipes f_0 can differ considerably from f_H. For example, the enclosure of Figure 3(b) may look like a

Helmholtz resonator, but the pipe is so long that it does not act like one. This can be clarified by calculating the Helmholtz resonance frequency of a simple Helmholtz resonator, given as:

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S_p}{L_p V_1}} \tag{1}$$

where L_p is the effective pipe length that includes an end correction needed to account for the complex acoustic radiation impedance of the pipe. If the parameters of Table 1 are used in Eq. (1), then we get f_H = 300Hz whereas the system has an anti-resonance frequency of f_b = 277Hz.

Helmholtz frequency	f_H	300	(Hz)
Resonance frequency	f_b	277	(Hz)
Front Volume	V_1	8	(cm^2)
Port length	L_p	120	(mm)
Effective Port length	$L_{p'}$	121.8	(mm)
Port radius	r_p	3	(mm)
Port Area	S_p	28.3	(mm^2)
Port losses	R_p	0.00031	(Ns/m)
Port losses	Q_p	30	(-)

Table 1: Fitted parameters of prototype pipe

Apparently the pipe is so long that we must use a transmission-line model, rather than applying Eq. (1). In the following we continue to denote the working frequency f_{work} by f_b, which applies for any length of pipe, in contrast to f_H, which together with Eq. (1) applies only to a system using a short pipe. We refer to a long pipe, somewhat arbitrarily, if $L_p > \lambda/10$, where $\lambda = c/f$ is the wavelength of the signal at the working frequency f. Mounting the pipe to a front volume V_1 has the advantages that the pipe length can be traded for the front volume without affecting efficiency at resonance, and that the driver diameter may be of a larger size than the pipe diameter, as shown schematically in Figure 3**.** Figure 4 gives the impedances and velocities occurring in the system's pipe of cross-sectional area S_p and length L_p. The band-pass system is modelled by a lumped-element model according to Figure . It is the combination of this front volume, the long pipe-shaped port, and the driver itself that enables an efficient resonant coupling between the driver and the acoustic load. We will discuss in the following the acoustics of the long port, which form an integral part of the resonating system. If the air is vibrating harmonically with a frequency corresponding to the wave number $k=\omega/c$ and velocity v_{p1}, then the input mechanical impedance Z_1 is given by[26]:

$$Z_1 = \rho_0 c_0 S_p \frac{\frac{Z_2}{\rho_0 c_0 S_p}\cos kL_p + j\sin kL_p}{j\frac{Z_2}{\rho_0 c_0 S_p}\sin kL_p + \cos kL_p} \tag{2}$$

The velocity at the end of the pipe is

$$v_{p2} = \frac{v_{p1}}{j\frac{Z_2}{\rho_0 c_0 S_p}\sin kL_p + \cos kL_p} \tag{3}$$

Looking at Eq. (3), we see that at frequencies such that $Z_2 \ll \rho_0 c_0 S_p$ and $\sin kL_p \sim 1$, v_{p2} can be much larger than v_{p1}. For these frequencies we get a gain of

$$\frac{v_{p2}}{v_{p1}} = \frac{\rho_0 c_0 S_p}{jZ_2} \tag{4}$$

It is this gain that we want to exploit.

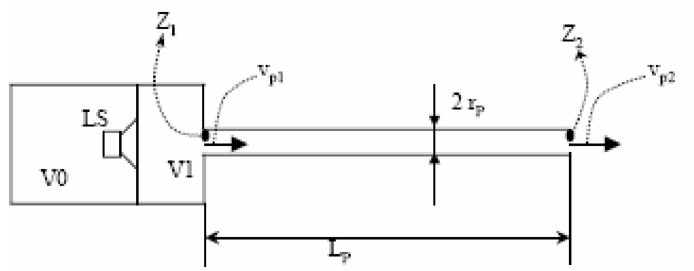

Figure 4: Mechanical impedances Z and velocities v in system pipe

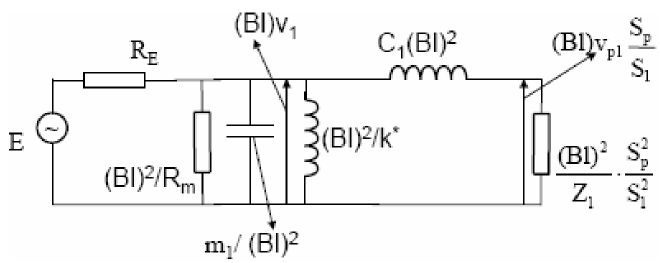

Figure 5: Lumped element model of system according to Figure 4

A loudspeaker in a pipe can be noisy. To reduce the noise a sound source of opposite phase can be used to cancel the original signal. Here it is assumed that the phase relating to the linear part of the acoustic field (the tonal sound) is of opposite phase with respect to both orifices of the pipes, like a dipole[26]. In the simplest form one pipe is acoustically connected to one side of the loudspeaker cone, and the other pipe to the other side of the cone, see Figure 6. The assumption is that the 'blowing part' does not add coherently and even contributes to the jet.

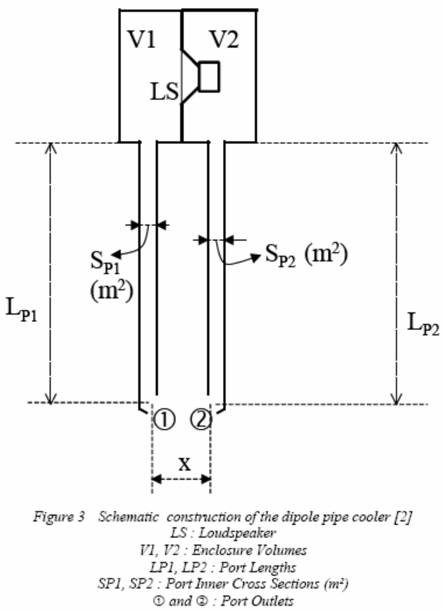

Figure 6: Dipole with noise cancellation

4. Numerical analysis of synthetic jets: challenges

From a design point of view it would be very valuable if numerical modelling could be used with confidence. Unfortunately, accurate numerical analysis of acoustic streaming phenomena is difficult due to the following reasons:

- Moving boundaries: non-linear diaphragm modelling required
- Very dense mesh required
- Microsecond to second temporal scales
- Large solution domain, much larger than the cavity
- From fully compressible to fully incompressible

There are many parameters that have to be optimised and we need numerically efficient methods to simulate these flows. A number of methods are described in literature, of which a selection of relevant papers is listed below.

4.1. Introduction

The traditional approach in Computational Fluid Dynamics (CFD) is to start with the Navier-Stokes (NS) equations. A major problem is turbulence modelling because it turns out that every approximation based on statistically averaging introduces a new approximation, the so-called closure problem. One way out is to solve the equations directly without any assumption about turbulence modelling (Direct Numerical Simulation (DNS)), however, because this involves the solution of all turbulence scales the grid requirements limit applications to the most simple of models. A popular method, certainly with the increased computer power right on one's desk, is Large Eddy Simulation (LES) that differs from DNS in resolving only the larger scales and assuming a model for the smallest scales. More computationally efficient but also less accurate are methods called Reynolds Average Navier Stokes (RANS). All these methods are based on solving continuum physics. Increasingly popular for multi-scale simulation approaches are methods that use the dynamics of particle density functions. Usually a distinction is made between Molecular Dynamics (MD) models and pseudo-particle models. The first group solves the interatomic forces and is obviously not very suited for the very large number of particles that occur in a dense gas. The second group is usually divided in off-lattice models and lattice-based models. Off-lattice models don't make use of a lattice, instead they use Monte-Carlo methods. A combination of MD and Direct Simulation Monte Carlo has been developed[27]. Lattice-based models include the older lattice gas automata and, more recently, lattice Boltzmann automata methods, of which the Lattice Boltzmann Method (LBM) is becoming quite popular, mainly because they are more numerically stable and computationally more efficient than Finite Volume or Finite Element solvers, in fact, orders of magnitude faster. An LBM comprises a set of nodes arranged on a Cartesian grid. The nodes are connected by links. Links are occupied by particles moving from one node to the next according to certain rules determined by density functions and scattering mechanisms. Repeated application of local rules for the motion, collision and re-distribution of pseudo-particles generates the resulting flow field. It can be proven that an LBM solution is also a solution of the NS equations. However, days of CPU time are still required!

4.2. Lower-order and hybrid models

Yamaleev and Carpenter[28] discussed a reduced-order model for simulation of synthetic jet actuators combining the accuracy of full numerical simulation methods with the efficiency of zero-order models. They demonstrated that the jet velocity strongly depends on the diaphragm frequency, due to fluid compressibility effects. Some favourable results have also been reported by Gallas et al. using a low-dimensional modelling approach[29, 30] and by Li using a reduced-order model and LES[31, 32]. Holman et al., [33] showed that the generally used dimensionless stroke length for estimating the governing parameters of a synthetic jet can be improved and formulated a general jet formation criterion based on the Strouhal number and the geometry of the orifice. They also performed a numerical study using a Cartesian grid solver for the NS equations. The advantage is that everything is modelled on a stationary mesh. A promising approach seems to be a hybrid solution using Euler equations for the cavity and full Navier-Stokes for the exterior[34].

Lower-order and analytically-based solutions are very useful for getting a feeling which parameter combinations govern the physics.

4.3. 'Traditional' CFD

LES and Unsteady Reynolds Averaged Navier-Stokes (URANS) simulations of the interaction of synthetic jets with a turbulent boundary layer are studied by a French group[35]. Fugal, et al., [36] used a commercially available CFD-code to study the influence of the exit geometry for a 2D planar jet using an incompressible, unsteady URANS-based solution strategy with a standard k-ε model. They concluded among others that the power required to form a synthetic jet is significantly smaller for a rounded exit compared to a sharp-edged exit.

4.4. Lattice Boltzmann Methods

Useful overviews can be found in Chen and Doolen[37] and two web-based sites[38, 39]. Haydock and Yeomans[40] described Lattice Boltzmann simulations of acoustic streaming as a steady flow field superimposed upon the oscillatory motion of a sound wave propagating in a fluid. An application of LBM to simulating the mechanism of sound generation in flutes was treated by Kuehnelt[41]. He discusses among others the problems with tracking both the sound field and the aerodynamic field, which propagate with disparate velocities and are weakly coupled. Wang and Menon[42] describe a hybrid approach coupling LBM for the jet formation and LES for the far field. In an extensive report Menon and Soo[43, 44] discuss DNS and LES of three-dimensional jets using LBM. One of their results was that in search for grid independence it was found that the solution beyond the cavity is highly sensitive to the resolution at the orifice. Unfortunately, despite significant improvements in solution time compared to DNS they quote multiple days of CPU time on a Cray multiprocessor massively parallel computer system.

The importance of synthetic jet numerical simulation is also demonstrated by the creation of a synthetic jet flow field database for CFD validation purposes[45]. Unfortunately, after reading this study one tends to become rather pessimistic about a useful approach for the foreseeable future due to overwhelming problems with sufficiently accurate experimental and numerical analyses related to a synthetic jet.

Conclusions

The paper discusses the principles of heat transfer and acoustics underlying synthetic jet technology for cooling purposes. Compared to fans, the benefits are highlighted and it is concluded that significant improvements can be expected in terms of heat transfer, acoustics, reliability and design freedom.

A loudspeaker in a special enclosure yields a resonant system enabling a large form factor design freedom cooling system. In addition it can be a compact, sensitive, and relatively efficient requiring a relatively low cone excursion, which makes the system very suitable for low-noise active cooling.

It is argued that numerical analysis is a must for future design optimization and several options are discussed. Unfortunately, it must be concluded that the state-of-the-art techniques are not suited outside university environments. A promising way to circumvent the numerical problems associated with synthetic jets is to adapt the theory of continuous jets.

Finally, if this technology takes off, it is obvious that the designer needs a compact model of a synthetic jet to be used in system level CFD analysis, akin to the way fans are currently handled.

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