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P. Dančová, Z. Trávníček, T. Vít

Summary: *Equipments which work on principle of SJ should be found in aerospace industry, in automotive industry, in design of pumps and ejectors, for cooling and heating applications, or for intensification of mixing in chemical reactors. The main advantage of these applications is relative simplicity of SJ equipment. This article introduces the most important works in SJ field. Out of short description of basic mechanism of SJ principle, main part of article is devoted to various field of SJ usage, as is jet vectoring, flow control in external and internal aerodynamics, intensification of heat transfer.*

1. Introduction

At the 2006 Geneva Motor Show the new sporty estate by Renault the Altica was presented. Most of studies like this are the demonstration of the virtuosity and professional skills of designers as usual, but this Renault Altica shows many new technical solutions as well. One of these solutions is application of equipment, which works on principle of so-called Synthetic Jet (SJ), for reduction of drag force and thereby decreasing fuel consumption. This SJ equipment, what consists of slot for air outflow and air sucking from surroundings, is inbuilt near to the trailing edge on the roof of the car Renault Altica. Authors of this car concept presume very optimistic value of fuel consumption reduction of about 15 percent, whereas the SJ equipment power requirement is only 10W (!) [1].

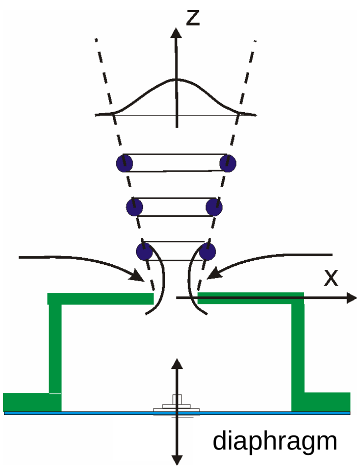

Fig.1 Principle of SJ

However the Renault Altica is only a pilot project likely never lunched into the series production lines, it shows clearly possibility of outcomes application from present fundamental research.

An example of similar application is a concept of Korean car company Kia Motors Corp. [2], when the car rear bumper is furnished by many circular nozzles which generate SJ (this idea hasn’t been presented in Europe up to the present days). Both of these concepts seem to be futurological at least but it has not been refused or neglected.

Equipments which work on principle of SJ should be found not only in automotive industry, but also in aerospace industry (where it helps to increase the lift force or to reduce aerodynamic drag), in design of pumps and ejectors, for cooling (electronics or gas turbine) and heating applications, or for intensification of mixing in chemical reactors. The main advantage of these applications is relative simplicity of equipment because there is no need

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Ing. Petra Dančová, Ing Tomáš Vít, Ph.D.: Katedra energetických zařízení, TU Liberec, Hálkova 6, 461 17 Liberec 1, mail: petra.dancova@tul.cz
Ing. Zdeněk Trávníček, CSc.: Ústav termomechaniky AV ČR, Dolejškova 1402/5, 182 00 Praha 8

neither of external flow source (e.g. compressor or fanner) nor incoming piping. It is pitty that by missing communication between scientists and engineers these equipments are not used much more in the practical applications.

2. History and present of SJ research

The first pilot works about problems of SJ are older than the term SJ has been established. One of the first successful applications was already described 50 years ago: Dauphinee [3] used the oscillating diaphragm for the air jet creation in the calibration equipment for temperature probe. The heat transfer on the wall in presence of SJ and the boundary layer control using SJ are described in the articles [4 and 5].

The creation of fluid jets by means of pulsating pistons was published by e.g. Mednikov and Novitskii [6] or Tesař [7, 8]. Some special applications as so-called “acoustic streaming” (see Meissner [9] and Lighthill [10]), flow caused by oscillating body (Stuart [11]; Davidson and Riley [12]), flow created by acoustic wave – whether stationary (Ingard [13]) or progressive wave (Lebedeva [14]) relate very closely to problems mentioned above.

Research connected with problems of oscillating flow and acoustic streaming has become a theme for intensive research at the end of 20th century. English term „Synthetic Jet“ was defined by Smith and Glezer in their paper *The formation and evolution of synthetic jets* in 1998 [15].

There has been extensive research in many important world laboratories at the beginning of the 21st century. For example we can mention some of the largest SJ research centers and some of their significant papers.

USA:	Georgia Institute of Technology [15–20, 57, 64]
	Georgia Technical Research Institute [16, 17, 19]
	Univ. of Wyoming [17]
	Boeing Comp. [17]
	Los Alamos National Laboratory [18, 21, 25]
	Utah State Univ. [21, 23, 25, 30]
	Univ. of Florida [22, 23, 28]
	George Washington University [23, 28]
	Univ. of Texas at Austin [24]
	Texas A&M Univ. [26, 27]
	NASA Langley Research Center [29]
	Auburn Univ. [31]
	Univ. of Washington [32]
Australia:	Univ. of Technology Sydney [33]
	Univ. of New South Wales, Sydney [34]
	Monash University, Melbourne [35, 36]
New Zealand:	Univ. of Auckland [37]
England:	Univ. of Manchester [38, 39]
	Univ. of Sheffield [39, 40, 55]
France:	CNRS [41, 42]
Italy:	Politecnico di Torino [43]
Japan:	National Aerospace Laboratory of Japan [44]
	National Institute of advanced Industrial Science & Technology [44]
Taiwan:	National Taiwan University [53, 58, 59, 67]
South Korea:	Seoul National University [45, 56]

Summary of institutions listed above should not be complete. There is a wide range of possible applications of SJ and there are many more research and industrial organizations which attend to problems of SJ.

Research of SJ whose quality can be compared to the top world research centers is also made in Czech Republic. Valuable research is made at the Institute of Thermodynamics AS CR since 2001. For example the article Trávníček & Tesař [48] is one of the first two known publications dealing with application of SJ for cooling. Other institutions which make research about SJ are e.g. Technical University of Liberec or Czech Technical University in Prague.

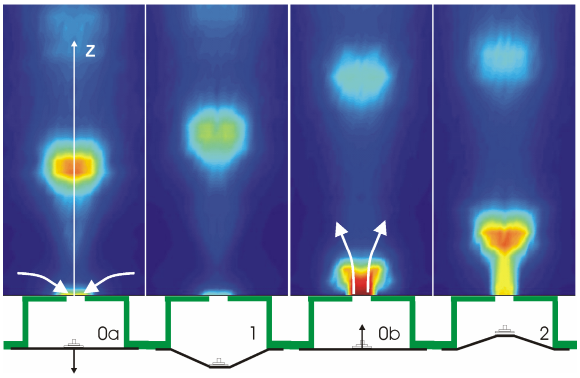
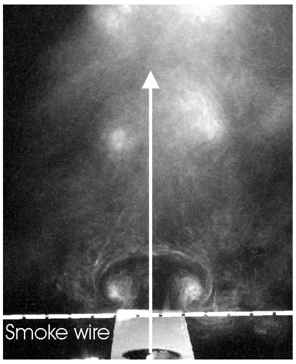
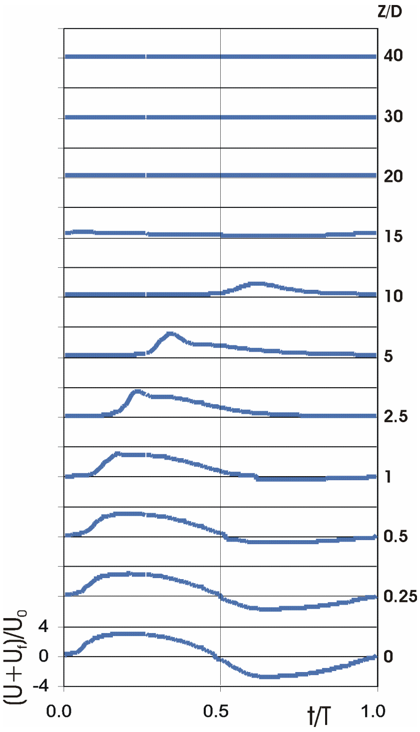


Fig.2 One of working cycle of SJ. Experimental results measured by CTA method with X-wire probe. 2→0a→1 suction; 1→0b→2 extrusion

The term “Synthetic jet” is translated to the Czech language like “Syntetizovaný proud”. This term was presented in 2002 [47] for the first time.





↑Fig.3 Creation of wortex rings by fluid extrusion from cavity of an actuator. Results of „Smoke wire“ visualization →Fig.4 Development of flow in nozzle axis during one cycle

3. Basic principle of SJ

Synthetic Jets are jets of fluid, which are generated by periodic pulsations of fluid. The oscillating force pushes and pulls this fluid through an orifice (nozzle) from cavity of an actuator. Vortex rings are formed at the lip of the orifice. These rings move with the velocity U_0 that must be high enough to prevent interaction with suction in the orifice. Vortex rings develop and dissipate and SJ has a character of free jet when it is far enough from the end of the orifice. The main advantage of SJ is the zero-net-mass-flux jet that eliminates the requirement of piping for the fluid inlet. Though the nozzle works with zero-net-mass-flux, the momentum in z direction is non-zero. The equipments for SJ can have different design, but the main mechanism and principle is mostly the same. Fig.1 shows simplest setting: There is some orifice on one end of the actuator, whereby the fluid is periodically sucked/exhausted to/from an actuator cavity. The pulsation generator of the fluid can work on principle of loudspeaker, piezo crystal, electromagnet, piston or other equipment. It is necessary to choose an optimal type and construction of actuator in relation to supposed working frequency range, working temperature, kind of working medium and required load of the unit.

Fig.2 shows the working cycle of SJ. Working cycle starts with diaphragm motion from zero position (position 0a) in $-z$ direction. This motion causes fluid sucking into actuator cavity. If the diaphragm deviation is maximum (position 1), the fluid is extruded from orifice of actuator. The biggest velocity of extrusion is in zero deviation of diaphragm (position 0b). Then the diaphragm moves in $+z$ direction to position 2. If the diaphragm achieves position 2, the fluid is sucked again and the cycle is repeated.

Fig.3 shows the vortex rings which are formed at the end of the orifice by fluid extrusion (2D case – there are formed counter-rotating vortex pairs, [15]). Fig.4 shows the development of flow in z direction.

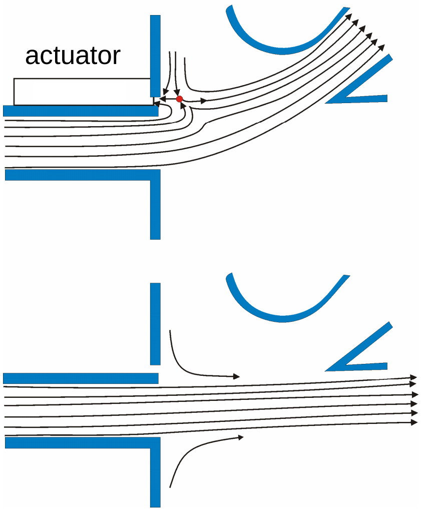


Fig.5 Fluid flow vectoring by SJ, A/ activated SJ, B/ closed SJ

For optimal function of SJ equipment it is important to choose driving frequency to work in resonance, i.e. eigen frequency of pulsating fluid column is the same or very close like eigen frequency of actuator. For equipment, which is actuated by pair counter-rotating oscillating diaphragms in air [49-51] it is possible to calculate this frequency from equality for kinetic and potential energy of equipment like:

$$f = \frac{1}{2\pi}\frac{d}{D}\sqrt{\frac{K_p}{2\rho L_e}}$$

d is an orifice diameter, K_p is stiffness of loudspeaker diaphragm [N/m3], D is diaphragm diameter and L_e is „equivalent length“ of fluid column (see [49]).

Equipment, which works at these conditions, will have the highest amplitude with the same power requirement (i.e. mass flow is the maximum by given power requirement).

There are some advantages of SJ: flow generation without requirement of manifold for operating medium. Even thought the time-mean mass flux through the nozzle is zero the momentum and the mass flux in the sufficient distance from the nozzle is non-zero. This feature of SJ helps us to place sources of fluid flow anywhere we want without the need of piping.

Another advantage, which is used in different applications, is a high value of turbulence intensity of generated fluid flow. This property is used mainly for heating or cooling.

4. Application

SJ has many significant applications and the number of application is increasing all the time. The most important applications can be divided into two main groups:

A) The main (primary) flow control

B) Using of stand-alone SJ or systems of them

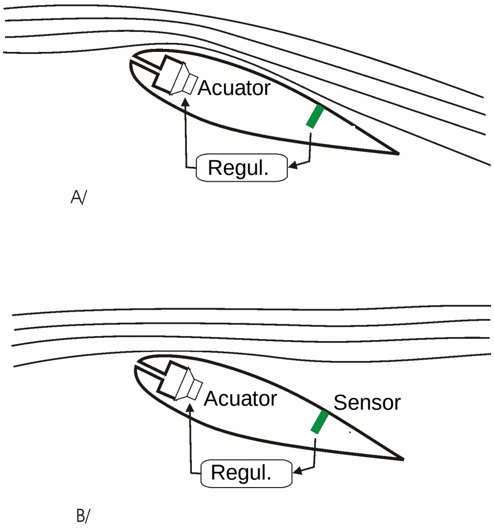


Fig.6 Using of SJ for lift force increasing on wing profile, A/ activated SJ, B/ closed SJ

A) *The main (primary) flow control*

A.1 Jet vectoring [18, 30]:

This category of applications includes the control of flow, which is parallel or perpendicular to the driving jet. Fig.5 shows the principle of jet vectoring. Fig.5a shows the case with activated SJ when the main flow is deflected from direct course and falls into so-called collector whereby leaves away. If the SJ is inactive main flow is not affected by SJ and has direct course (fig.5b). The equipment, which works on this principle, can be used for example in air distributors. In this case the SJ equipment is driven by electric current only. This equipment which is able to vector substantial flow volumes works without need of complicated mechanical components. Details about this application of SJ should be found in [18] or [30].

A.2. Flow field control in external aerodynamics:

For example it is control of turbulence and control of boundary layer separation. It can be used for a drag reduction, increasing lift force or for noise decreasing [17, 19]. One of applications is concept of Renault Altica [1] (which is mentioned above). Other applications of SJ are possible to find on airfoils [44] (Fig.6) or propellers of helicopters, some of these examples are inscribed as „virtual shaping effect“ of airfoil [28, 29].

So-called „smart control“ of the airfoil shape is intensively discussed presently. This equipment allows adapting of main characteristics of the airfoil to instantaneous conditions in the boundary layer or to the requirements of external control unit. It is possible to improve airfoil parameters and the system maneuverability or to simplify or completely remove mechanical control systems on wings. These technologies are a special perspective in small and very small pilotless planes (Micro Air Vehicle MAV, Unmanned Aerial Vehicle UAV), eventually in analogous underwater vehicles (Autonomous Underwater Vehicle [53]).

The other perspective application of SJ is focused on improvement of wind power plant propellers characteristics (presently analyzed at IT CAS). The main objective of this research is to increase lift to drag ratio and to decrease aerodynamic noise [54,55].

Example of SJ flow influence on aerodynamic drag of “bluff body” is described in [56]. Fig.7 shows results of numerical simulation of flow past a bluff body, which has nozzles at the trailing edge. These nozzles alternately push and pull flow of fluid. This figure shows flow field past rectangular bluff body in case a/ nozzles don’t work, b/ nozzles work in phase, i.e. nozzles push fluid at once and pull fluid at once, c/ nozzles work in antiphase, i.e. if one of nozzles push the fluid, the second pull the fluid and conversely. Results show ability to decrease drag coefficient for about 25 percent with application of this equipment. It is necessary to regulate frequency and power of SJ in relation to fluid velocity to achieve optimal drag reduction. The rectangular profile should represent a car model in this case.

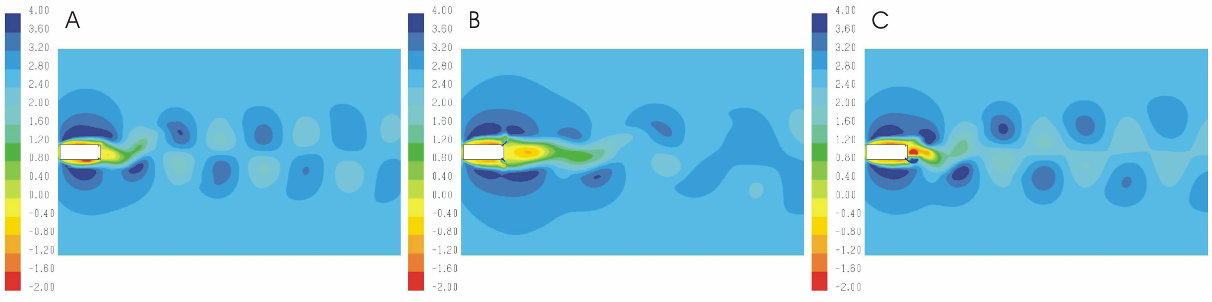


Fig.7 Wake past bluff body (numerical simulation), A/ without SJ, B/ SJ nozzles work in phase, C/ SJ nozzles work in phase opposition

A.3. Flow field control in internal aerodynamics:

Turbulence control and control of boundary layer separation is another typical example of SJ application. Fluid flow through wide-open diffuser, which is susceptible to separate from the wall, can be stabilized by SJ [42]. Suppression of undesirable flow separation increases efficiency effectively and decreases power loss.

A.4. Increase of mixing intensity has importance in many chemical processes, such as in combustion [42]. Typical setting is numerically solved in paper [57]: The air and fuel flows move into combustion chamber where SJ improves their mixing. It is possible to improve parameters of the combustion equipment, e.g. to increase power, to decrease Noxious emissions, or to decrease overall dimensions eventually.

A.5. Increasing of heat transfer due to main flow control:

Very interesting example of application of SJ is cooling of electronics with very small dimensions [34] (Micro-Electro-Mechanical Systems, MEMS). In these small dimensions there is often laminar flow and heat transfer is unacceptably small. Numerical study [34] simulates intensification of electronic processor's cooling: the laminar airflow is heated from one-side and affected by SJ from other side. Laminar flow is disturbed by SJ (authors discuss pseudo-turbulence). For proper setting and for proper flow parameters the study [34] shows how it is possible to improve processor cooling.

B) Using of stand-alone SJ or systems of them

B.1. Action of force for control of motion, e.g. for autonomous vehicle in the water and in the air.

Recently, there were developed new generations of SJ generators, in particular hybrid SJ and double-acting SJ [58-62] (IT CAS, TU Liberec, Univ. Sheffield a National Taiwan Univ.). The purpose of these works has been improvement of SJ, in particular on the field of electronics

Fig.8 Principle of valveless pump

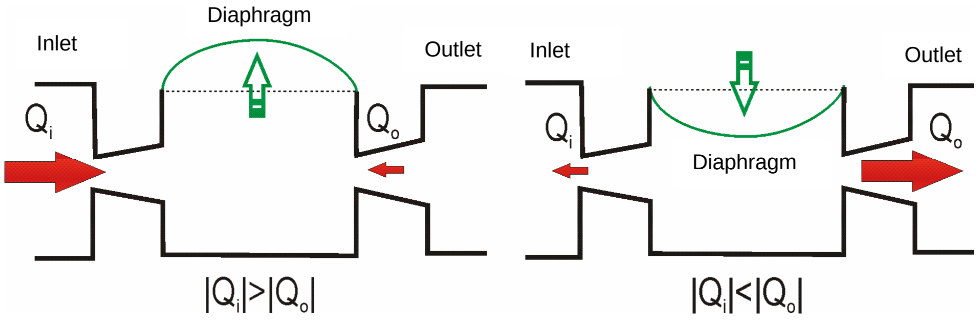
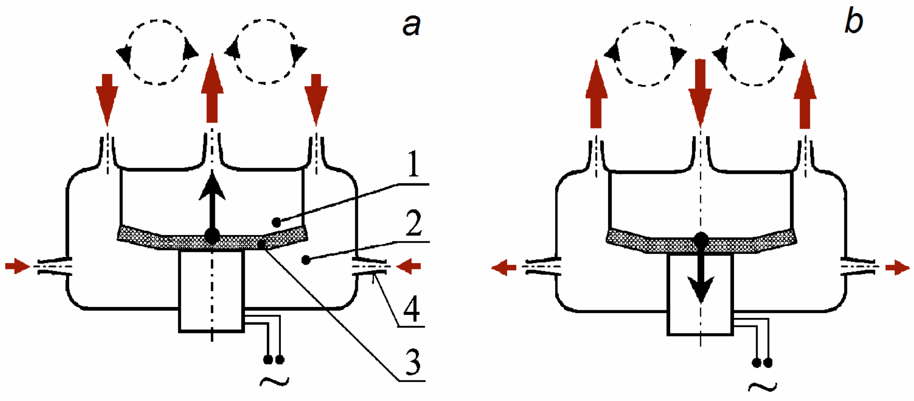


Fig. 9. Double-acting hybrid synthetic jet actuator



cooling. In addition to the improved geometry of SJ generator can be used for nozzle design for autonomous underwater vehicle (AUV).

Function of SJ in the water is specific. Though SJ in the water works in relative low frequency (some tens of Hz by macroscopic scale of centimeters), gases dissolved in the fluid are released, cavitation increases due to considerable acceleration of fluid on actuator surface. The decrease of the pressure in the actuator leads to the formation of cavitations bubbles. These bubbles affect adversely the stiffness of the actuator and operation of SJ. The problems connected with the SJ in the water are solved at the TU Liberec nowadays.

B.2 SJ used for intensification of the heat transfer

This group of applications contains cases as impact SJ [4, 20, 48, 50, 51] and cases of complex fluid fields generated by SJ only [64]. A pulsation of the jet together with the high level of turbulence intensity leads into the strong increase of the heat transfer coefficient when the equipment is designed properly and the heated or cooled surface is placed in the right position. Due to this advantage there is a wide range of applications in the field of cooling of heavy thermally loaded parts in electronics or for cooling of blades in combustion turbines. More details about these questions are possible to find in e.g.[50, 51, 58-62]

Combination of SJ with pump or ejector brings other options. Fig.8 shows an example of valve-less pumps design [65]. This valve-less pump consists of two diffusers and of chamber with actuator. Diffusers are optimalized to have bigger drag in one direction than in the opposite direction. Periodic motion of actuator produces sucking of fluid by first of diffusers and extrusion by second of diffusers. This equipment is able to have very heavy duty by very small size. Improvement in particular is by MEMS systems.

An idea to combine SJ and valve-less pump led to design of hybrid synthetic jet actuator [66]. Fig.9 shows a design of double-acting hybrid synthetic jet actuator. Fig.9a shows period of extrusion from front chamber (1), if the fluid is sucked simultaneously in back chamber (2). Opposite period (sucking into front chamber) is shown on fig.9b. Resulting flow has time-mean mass flow of fluid in actuator non-zero – it enables to achieve better results in noted applications [58,59].

5. Conclusion

Equipments, which work on SJ principle, have simple construction and many advantages. It depends on ingenuity and confidence of designers and managers if they resolve to use new technologies in their products.

6. Acknowledgment

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