On Some Recent Applications of the Coanda Effect

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Over the last quarter century or so, the Coanda principle has become increasingly used in a wide variety of applications, including industrial, medical, maritime technology, and aerodynamics. In addition, its effect has been increasingly observed in the natural world. Devices employing this principle usually offer substantial flow deflection, and enhanced turbulence levels and entrainment compared with conventional jet flows. However, these prospective advantages are generally accompanied by other significant disadvantages such as jet flow detachment, and a considerable increase in associated noise levels. Much of the time, the reasons for this are not well understood. Consequently, in many cases, the full potential offered by the Coanda effect is yet to be completely realized. This paper discusses a variety of recent applications of the principle and describes attempts to understand some of the difficulties associated with it, particularly those related to increased acoustic radiation.

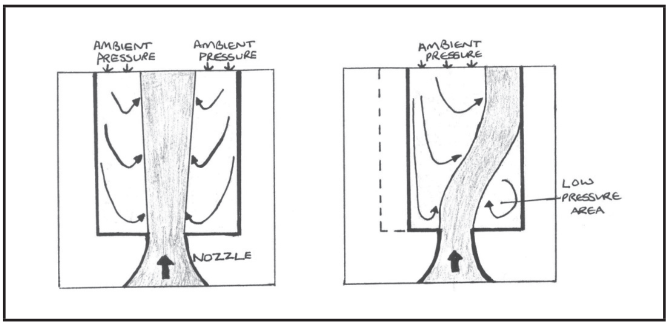


Figure 1. The Coanda effect. (*Image by Caroline Lubert, based on image from Scientific American, December 1964, pages 80–88*).

1. THE COANDA EFFECT

The Coanda effect is a phenomenon that was first observed in 1910 by a mathematician and engineer named Henri Coanda.[1,2] He discovered that when air was ejected from a rectangular nozzle, it would attach itself to an inclined flat plate connected to the nozzle exit. Emphasizing the need for a sharp angle between the nozzle and the flat plate, Coanda then applied the principle to a series of deflecting surfaces, each at a sharp angle to the previous one, and succeeded in turning flows through angles as large as 180°. He stated that "when a jet of fluid is passed over a curved surface, it bends to follow the surface, entraining large amounts of air as it does so," and this phenomenon has become known as the "Coanda Effect."[1] The effect is a result of entrainment of the ambient fluid (liquid or gas) by the similar-phase primary jet. When there is a proximate surface, a low pressure region develops as entrainment of the ambient fluid by the jet removes fluid from the region between the jet and the surface, causing the jet to be deflected toward the wall, as shown in Fig. 1. The balance between the inward radial pressure gradient (suction force) and the outward centrifugal (inertial) force then holds the jet to the wall. The Coanda effect can also be demonstrated without the presence of a solid surface using two adjacent lighted candles. The rising heated air from each candle is attempting to entrain the (common) ambient air in the area above and between the flames, causing the two smoke streams to be deflected toward one another.

It should be noted that the term "Coanda effect" is often used incorrectly. Recall that a key requirement for the existence of this phenomenon is that the primary jet and the surrounding fluid must be essentially the same substance (e.g., a gas jet flowing into a body of gas, or a liquid stream discharging into an ambient liquid). Thus, the commonly observed phenomenon whereby the back of a spoon is placed in a flowing stream of water and is observed to be pulled into the stream (as shown in Fig. 2) is clearly not an example of the Coanda effect, since there is no ambient liquid available to be entrained into the water stream. A more accurate name for this phenomenon would perhaps be the "teapot effect," after the related occurrence in which liquid poured from a teapot often runs down the outside of the spout and drips from the base of the teapot.[3,4] This frequently experienced phenomenon is often attributed to either surface tension or the adhesion of the liquid to the container surface. However, in fact the phenomenon appears to depend on the associated flow regime. First, consider large-scale (rapid) regimes, in which case both the Weber number (a measure of the relative importance of the fluid's inertia compared to its surface tension) and the Reynolds number (which measures the ratio of inertial forces to viscous forces) are significantly greater than one. In this case, surface energies are negligible, and therefore, surface adhesion effects are minimal. Keller and others argue that there are in fact two mechanisms at work: the bending of streamlines and flow separation.[3] At the lip of the teapot, the liquid velocity is greatest and so (by Bernouilli's principle) the liquid pressure is lowest. The correspondingly greater atmospheric air pressure then pushes the liquid against the lip, so that it flows around it and turns the corner. The surrounding air then supports the flow along the underside of the teapot, although this flow is unstable and eventually detaches from the surface at a point determined by the flow characteristics. In small-scale regimes, on the other hand, capillary effects are expected and the influence of wettability has been shown by Kistler et al. and others to be of paramount importance.[4] More recent work suggests that wettability is also important in the separation of rapid flows,[5] and this result, if correct, bridges the gap between small (surface) and large (flow) scales. A comprehensive discussion of this flow is given in Howe.[6]

When a jet attaches to a convex surface as a result of the

Figure 2. The Teapot effect (*Image by Axda0002 at en.wikipedia [CC-BY-SA-2.5 (www.creativecommons.org/licenses/by-sa/2.5)], via Wikimedia Commons*).

Coanda effect, the accompanying longitudinal curvature yields increased entrainment and jet growth compared with a wall jet on a plane surface. Indeed, experimental results indicate that Coanda jets can entrain as much as twenty times their own volume whilst following the curved surface.[2] This effect can be used to provide vehicle propulsion and lift. A Coanda jet blowing over the front of an appropriately curved body causes entrainment of the surrounding fluid, which in turn generates a relative vacuum in this location. The higher (atmospheric) pressure at the rear of the body then impels it forward. This process, which is commonly referred to as negative drag, is the opposite of a standard propulsion system that utilizes a force at the rear of the body to propel it forward against the resistance of the fluid in front of the body. A similar principle can be applied as a means of generating lift. Clearly one of the most serious problems in the application of the Coanda effect is jet flow detachment, which can occur for many reasons.[5] For example, if shock waves are formed inside the jet plume, jet flow detachment from the solid surface occurs because of shock wave- boundary-layer interaction. Thus, much recent research has focused on methods for delaying or preventing this detachment, or breakaway. For example, since the detachment is a result of a high static pressure at the nozzle exit, it can be slowed by lowering the exhaust static pressure (by using a divergent nozzle). In fact, it can be delayed considerably by the use of a convergent-divergent nozzle.[7] Indeed, the potential benefits, including enhanced turbulent levels and increased entrainment, overshadow the disadvantages associated with devices utilizing the effect. This explains the existence of numerous examples of the Coanda effect in nature and the abundant and growing number of man-made uses of the principle.[8]

2. APPLICATIONS OF THE COANDA EFFECT

Some of the most significant applications of the Coanda principle are in the fields of aerodynamics, marine technology, and industry. The effect is also beginning to be more commonly recognized as responsible for observed phenomena in the natural world, and this will be discussed along with the recent utilization of the Coanda effect in other, novel applications. Finally, a more detailed discussion of recent work in aeroacoustics will be presented, including details of a recently developed model for predicting the aeroacoustic characteristics of a three-dimensional turbulent flow over a particular Coanda surface.

2.1. Application to Aerodynamics

The Coanda effect has been used in aircraft design since the mid 1950s and is still in use today. As one of the most efficient methods of generating increased lift, the Coanda effect has many applications in aviation and navigation. Two aerodynamic applications where the principle has been used successfully for some time are in circulation control devices and in thrust vectoring. Two of the most recent applications have been to the B-2 Spirit stealth bomber (in 1997) and the F22 Raptor fighter aircraft (in 2005). The former is an aircraft specifically designed to employ stealth technology to penetrate anti-aircraft defenses. The B-2 exhaust ducts have curved profiles, which flatten out to wide slits and open out into over-wing trenches. The Coanda effect is exploited to direct the thrust aft (towards the rear) whilst simultaneously concealing the nozzle openings from direct rear view. The F22 relies on the thrust vectoring capability offered by the Coanda principle to perform maneuvers not possible in conventional fighter aircraft.

2.1.1. Airfoil Circulation Control Devices

Over recent years, a great deal of effort has been put into modifying aircraft wings and wingtip configurations to improve performance. Conventional airfoils derive lift from the circulation produced by the pressure differential between the lower and upper airfoil surfaces and typically have poor lift characteristics. In contrast, a circulation control airfoil (CCA) produces lift by the use of Coanda surfaces and slot blowing. A small high-speed jet is blown over a rounded (Coanda) airfoil trailing edge. The rounded contour (in contrast with conventional airfoils, which are cusped) promotes the Coanda effect, and the flow separation point at the airfoil's trailing edge is displaced downwards. The jet flow over the contour creates a relative vacuum via the Coanda effect (as explained previously), producing circulation and thus lift. The displacement achieved depends entirely on the momentum of the blowing jet. In one such study, Simpson investigated the improvement of a wing's aerodynamic efficiency by the use of Coanda tip jets.[9] Simpson determined that use of a Coanda jet, blowing outward from the wing tip region of a lifting wing, yielded a significant increase in the lift-to-drag ratio for the higher lift coefficients, compared to the jet geometries used in previous studies. Related experiments have confirmed such circulation control wings (CCW) to be effective in offering significant lift enhancement compared with conventional airfoils.[10] CCW technology is one of the most important potential applications of the Coanda effect, and it has been successfully incorporated into the design of a number of aircraft including a prototype Boeing 707, the Hawker Siddeley Buccaneer, and a modified Northrop Grumman A6 Intruder. Other significant benefits offered by airfoils with Coanda trailing edges include a considerable reduction in wake fluctuation at high angles of incidence compared with standard airfoils and improved stability at the wake boundary.[11] Extending the design further such that the Coanda surface is moveable facilitates the formation of two (upper and lower) slots, yielding the same bidirectional control as a device with a conventional mechanical flap, but without the need for a flap.[12] Unfortunately, a major disadvantage of this technique is that it requires additional Auxiliary Power Units (APUs) or engine capacity in order to supply the bleed air for the slot blowing. Engine and APU manufacturers are trying to address this problem by designing APUs that would supply all of the bleed air so that engines would be dedicated to providing thrust only. However, achieving this would first require a significant improvement in APU reliability.

2.1.2. Thrust Vectoring

Thrust vectoring is the ability of an aircraft (or other vehicle) to direct the exhaust thrust from its main engine(s) in a direction other than parallel to its longitudinal axis. It allows VTOL (vertical take-off and landing) or STOL (short take-off and landing). The principle of thrust augmentation due to the increased mixing associated with the Coanda effect is well understood[2, 13], and this principle enables aircraft such as the F22 Raptor fighter to perform various maneuvers that would not otherwise be possible. The design of high-performance thrust-vectoring exhaust nozzles is extremely complex.[14] Of particular concern is the issue of jet flow detachment, and a great deal of recent work has focused on this issue. For example, supersonic jets are commonly over- or under-expanded and the adjustment of (increase or decrease in) the jet pressure to the pressure outside the nozzle results in a system of shock waves being formed inside the jet plume. The interaction of the jet with these shock waves can act to precipitate jet flow detachment from the solid surface. Bevilaqua et al. performed one of the few supersonic Coanda jet studies.[15] In their work they tried to improve thrust vectoring by designing a supersonic nozzle in which the Coanda effect could be used to deflect the engine exhaust jet. They examined the effect of exhaust nozzle geometry and designed a convergent-divergent nozzle which eliminated the expansion shocks and significantly improved thrust vectoring compared with other conventional convergent nozzles in use at the time. Cornelius and Lucius subsequently performed an experimental study of a two dimensional under-expanded supersonic Coanda jet flow around a circular cylinder.[16] They confirmed the results of Bevilaqua, determining that jet flow detachment could be significantly delayed by employing a convergent-divergent nozzle. In related work, Sawada and Asami performed a numerical study on an under-expanded supersonic Coanda jet flowing around a circular cylinder.[17] They solved the Navier-Stokes equations in two and three dimensions. The result of their two-dimensional calculation yielded rather poor quantitative agreement with existing experimental data. They posited that this was due to their model's omission in the model of the significant three-dimensional structure observed to develop, because a preliminary three-dimensional calculation provided better agreement and revealed the considerable influence that the surface had on the flow field. As a result of these and other studies, most current aerodynamic applications of the Coanda principle utilize convergent-divergent nozzles.

Unfortunately, most effective thrust-vectoring design concepts depend on the use of actuators with variable geometry, which is in direct opposition to other desirable design goals since actuators add both weight and complexity to the aircraft. Thus an alternative area of research has focused on fluidic thrust vectoring concepts, many of which utilize the Coanda principle.[18, 19] The basic concept is to inject a secondary sheet of air along a curved sidewall flap and, via entrainment, to draw the primary jet in the same direction as the injected jet, thus producing yaw thrust vectoring. Unfortunately, this has so far proven to be largely unsuccessful. The largest thrust angles were produced at low nozzle pressure ratios (NPR), where the primary jet momentum was minimal near the sidewall flaps. As the NPR increased, the pressure gradient—which is crucial to the Coanda effect—disappeared.[18] It is postulated that the high aspect ratio of the nozzle may have impeded the effectiveness of the thrust vectoring concept, and work on this promising concept is still ongoing.

2.2. Industrial Applications

There are many areas in engineering where the Coanda principle has been used to great effect including turbines, cooling processes, and galvanizing techniques. A turbine is an engine which extracts energy from a fluid flow and converts it to useful work. There are two main types of turbine. Impulse turbines change the direction of flow of a high velocity liquid or gas jet, whereas reaction turbines (as implied by the name) develop torque and are turned by reactive forces rather than by a direct push or impulse. A new kind of reaction turbine, driven by the deflection of a jet along a curved wall due to the Coanda effect, was described by Teodorescu-Tintea in his PhD thesis and other work.[20–23] In this turbine, the fluid, combustion gas, or hot air is discharged through nozzles on a rotating hollow shaft. It is then deflected along adjoining backward-curving (Coanda) blades. The resulting forward reaction force drives the system. In contrast to other reaction turbines, the fluid does not flow in a channel but along the convex surface of a blade which provides the additional benefit of facilitating the cooling of the surface. Impulse turbines work by discharging a water jet into air through a nozzle and directing it onto curved buckets which extract energy and convert it to work. Modern impulse turbines successfully employ the Coanda effect to adhere the high-speed jet to the back of the appropriately curved (Pelton turbine) buckets, creating a lift force and an associated angular momentum (in the sense of rotation), which yields an increased torque compared with a system using a regular bucket.[24]

The same principle used to cool the reaction turbine blades is used to cool circular cylinders, which are present in many industrial circumstances. This is traditionally achieved by placing the cylinders in an unlimited uniform parallel air stream with negligible turbulence in the main stream, but the principle can be considerably improved by locating the cylinder symmetrically in a two-dimensional finite-width jet.[25] The Coanda effect causes the jet to adhere to the cylinder, and the associated heat transfer can be increased by up to 20 % in this way.

Swirl atomizers are devices for breaking a liquid into small droplets. Typical applications include agricultural spraying machinery and oil-fired furnaces. The droplets are the result of the breaking of the liquid sheet under the action of internal turbulence. Air is blown through the middle of the nozzle, and swirling liquid is passed over the nozzle lip. Clearly this process is an example of the teapot effect rather than the Coanda effect, since it involves two non-similar-phase fluids. However, the results are still of some interest. For example, with a sharp-edged lip, the atomization is found to be poor, but when a curved lip is used, good atomization is ensured.[26] In a related problem, Lee et al. studied the effect of using a Coanda nozzle (rather than a regular nozzle) in a process for putting a galvanizing layer on a metallic strip.[27] Using a regular nozzle causes "splashing" and an uneven layer on the strip. Using a Coanda nozzle instead causes the wall shear stress to be increased due to the deflection of the jet by the teapot effect as it leaves the nozzle. This causes the potential splashing region to be moved further downstream out of range; therefore, the problem of splashing is removed, and the whole galvanizing process is improved.

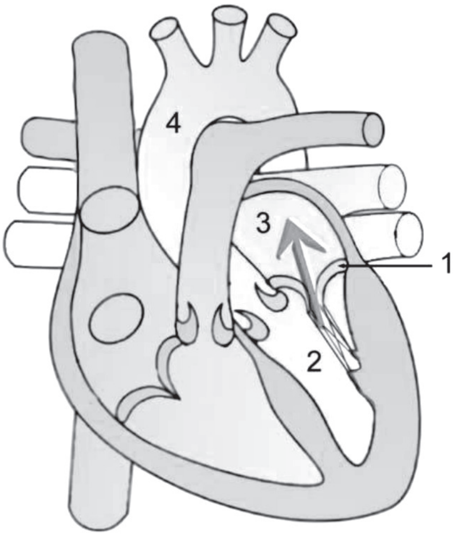
2.3. Medical Applications

The Coanda effect is an established physical phenomenon of fluid flow which has practical relevance in the medical field. Two applications in which it is particularly prevalent are Cardiology and Artificial Respiration. In the former, the Coanda effect is generally a beneficial physiological effect; although, one must guard against the misdiagnosis of cardiac irregularities due to the appearance of potentially misleading phenomena resulting from the Coanda principle. In the latter, the Coanda effect can lead to advantageous developments in the design of artificial respiration devices.

2.3.1. Cardiology

In cardiovascular medicine, the Coanda effect is responsible for the two separate streams of blood in the fetal right atrium.[28,29] Both streams are mutually important and play an essential role in fetal circulation and development. However, it is critical that the streams remain separate, or they could destructively interfere with one another, with severe consequences. As a result of the convex geometry of the right atrial muscular anterior wall, the Coanda effect ensures that the streams are kept apart.

However, the Coanda principle can also have negative implications, particularly in the context of medical diagnosisc.[30] The Doppler effect refers to the well known apparent change in frequency experienced when a sound source is moving relative to an observer. If high-frequency sound waves are reflected from a moving flow, such as blood in an artery, the detected change in frequency can be used to determine the speed and direction of the flow. This process forms the basis of Doppler ultrasound, and colors are often used to indicate the direction of the flow. Color Doppler echocardiography is an imaging technique that is extensively used in clinical applications since it not only allows doctors to easily and non-invasively evaluate the heart valves, but it can also detect abnormalities such as the backward flow of blood through partially closed heart valves (so-called valvular regurgitation). Mitral regurgitation is the most common form of valvular heart disease and is invariably fatal if not detected. It is a disorder in which the mitral valve does not close properly when the heart pumps out blood, causing a jet of blood to leak (regurgitate) back into the left atrium. As a result of the Coanda effect, such jets (known as wall-hugging jets) are then typically dispersed along the adjacent curved left atrial wall (shown in Fig. 3), and consequently their presence is often missed or underestimated by color Doppler imaging, which focuses on the more readily apparent central jets.[31,32]



1. Mitral valve; 2. Left Ventricle; 3. Left Atrium; 4. Aorta.

Figure 3. Schematic drawing of Mitral regurgitation. (*Image by J. Heuser; JHeuser [CC-BY-SA-2.5-2.0-1.0 (www.creativecommons.org/licenses/by-sa/2.5-2.0-1.0)], via Wikimedia Commons*).

2.3.2. Artificial Respiration

The ability to provide sophisticated control using a fluid logic device based on the Coanda effect, rather than using mechanical parts, offers tremendous potential in a medical environment. The general principle is that a free jet flowing in a diverging channel can attach itself to either wall, and it can be forced to separate from one wall and attach instead to the other via the Coanda effect. (The effect essentially changes the low pressure area to one of relatively high pressure.) This is accomplished using small auxiliary jets flowing through holes in the walls. Thus, a fluid logic device is analogous to a "monostable flip-flop" in electronics. Fluid logic devices have been used to great effect in artificial respirators and other applications for many years.[33,34] Indeed, they were the cover story in *Scientific American* as long ago as December 1964. The Coanda principle has also been used to smoothly and efficiently guide air and liquids into tubes and cuffs for ventilation purposes.[35] However, the same principle may clearly be potentially detrimental in some cases. For example, Qudaisat has reported the occurrence of unequal inflation of the lungs during artificial ventilation of a paralyzed and intubated patient using a single-lumen tracheal tube, and he hypothesizes that this may have resulted from the Coanda effect occurring in the trachea and preferentially attaching air in one direction.[36]

2.4. Application to Maritime

There are numerous occasions in marine engineering where the Coanda effect can be used to enhance performance, particularly in low-speed ship maneuvering and dynamic positioning. However, there are also many examples of it being experienced by both floating and submerged vessels as an unwanted side-effect when, according to English,"its presence usually detracts from performance."[37]

2.4.1. Propulsion

Vessel propulsion is one example of where the Coanda principle can have a negative impact. The force on the vessel that a propeller generates is proportional to the speed, volume, and direction of the water jet exiting the propeller. When the vessel moves through the water, the propeller jet's direction is changed by the Coanda effect, causing it to follow the shape of the ship's hull. This can significantly curtail the propeller's efficiency. A similar problem occurs when a ship is being handled at low speed. In this case, when trying to go astern, the nonsymmetric flow and pressure on the hull can cause the Coanda effect to produce a turning moment on the ship that may not be predictable.[37] In order to try to mitigate such losses, anti-Coanda methods have been suggested for separating both the jet-water-stream flow field and the supporting ocean-water flow field from the vessel hull by altering the load-bearing properties of the hull to change it from a buoyant surface to a hydrodynamic surface.[38] However, this proposed solution is obviously extremely costly and complex, and has not been widely implemented to date. A more practical solution in many circumstances is to increase the ship's speed, thereby utilizing the well known property of the Coanda effect that entrainment of the surrounding fluid is reduced when the primary jet is ejecting into a coflowing stream as opposed to a stationary stream.

2.4.2. Hydrofoils and Sumbersibles

The principles governing airfoil circulation control devices discussed previously (Section 2.1.1: Airfoil Circulation Control Devices) can also be applied underwater. A hydrofoil is a watercraft which operates in a similar way to an airfoil. As the vessel increases in speed, the foil develops sufficient lift to raise the hull out of the water, typically resulting in a drag reduction and further increase in speed. Clearly, hydrofoils employing the Coanda effect via nozzles emitting water jets along the leading edge of the appropriately-shaped foil will create the well-known "negative drag" associated with the principle (Section 1) and cause the hydrofoil to be self-propelling.[2] Howe studied in detail the noise associated with the circulation control of a hydrofoil by a Coanda wall jet.[39] As discussed previously, the advantage of such devices is that the associated lift can be greatly increased (even at low mean speeds) without the need for mechanical apparatus. However, the relatively high jet speeds needed to maintain attached flow around the hydrofoil lead to at least one additional noise source. The noise at the trailing edge of the hydrofoil is then identified as comprising three principal components, namely "curvature noise," trailing edge noise, and "passive slot noise." Theoretical predictions of the associated acoustic radiation contributions are made and are found to be "critically dependent on a proper understanding of the turbulence characteristics of the flow, especially within the Coanda jet."[39] This is common in aeroacoustics and will be discussed in further detail in Section 3.

Underwater exploration has always been hampered by the difficulties of propelling a submerged vessel efficiently and economically, due to fluid resistance. Over the years, considerable work has been carried out on the design and testing of fully submersible vehicles that utilize the Coanda effect similarly to an airfoil or hydrofoil.[40,41] Results indicate that such devices do indeed yield some advantages over conventional methods of propulsion, in terms of both vehicle maneuverability and the reduction of drag. However, these advantages do not appear to be significant compared with the associated difficulties, and consequently, other areas of research focusing more directly on drag reduction have been pursued instead.

2.4.3. Ship/Structure Interactions

According to the results of physical modeling by English, "...interactions arising from the Coanda effect are not restricted to the propulsors and hulls of individual ships, but can be experienced by ships interacting with each other and with fixed structures...."[37] For example, when towing ships in restricted waterways or berthing large ships near jetties with solid walls, it is critical to notice where the wash from the ship's propeller is aimed. If it is directed at a glancing angle to another ship or a solid wall, the Coanda effect could change the pressure distribution on the hull and cause the ship to turn unexpectedly. Since increasing the speed is rarely an option in these circumstances, solutions to this problem currently rely on the experience and expertise of the ship's captain.

2.5. Application to the Natural World

There are multiple instances of where the principle of fluidics under discussion here is observed in the natural world. One such example is topographically directed winds.[42] For example, in the Moldavian Plateau in Romania, an arc is formed by the Carpathian and Transylvanian Alps, and the Coanda principle causes northerly air streams traveling around this arc to be diverted toward the southwest (with an associated low pressure area further to the southwest). This, together with the föhn effect (a dry down-slope wind which occurs in the lee of a mountain range), causes a surprisingly Mediterranean-like microclimate to be located in this part of the Danube Valley, proving extremely advantageous to local farmers and residents. A second, less beneficial example occurs in Big Delta, Alaska, U.S.A., where a local wind, described as similar to "...a stream of water coming from the nozzle of a hose...," is observed when east-southeast or southerly winds are blowing.[42] Such winds tend to obey the Coanda effect and follow the curve of the Alaska Range rather than flowing directly onto the Tanana Plain as would be predicted. It should be noted that the behavior of the Rhone Valley Mistral in France could also possibly be explained by the Coanda effect, since after blowing along the curved east side of the Rhone delta, it changes direction

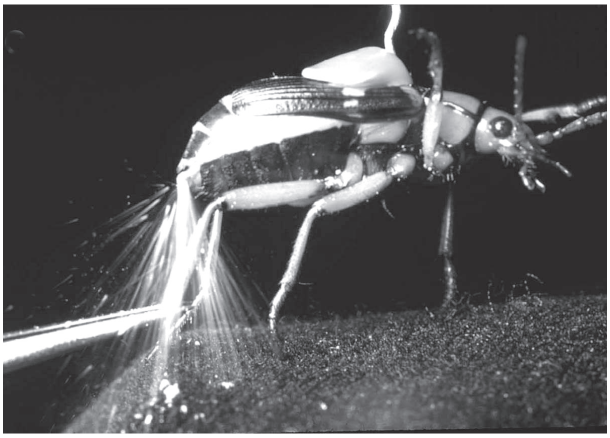


Figure 4. The Bombardier beetle and the teapot effect. (*Image reproduced by kind permission of Thomas Eisner and Daniel Aneshansley, Cornell University*).

unexpectedly from northerly to north-northwest as it hugs the Alps. Clearly, a greater understanding of the underlying principle causing these observed effects is crucial to future economic development in such regions.

In a fascinating example of the teapot effect (incorrectly identified in their work as the Coanda effect), Eisner and Aneshansley report that Bombardier beetles eject a defensive fluid (a hot quinine-containing secretion) when disturbed, and “rely on the Coanda [sic] effect for aiming.”[43] Such beetles, which are members of the family Carabidae, have flanges (diagnostic for the subfamily Paussinae) behind which is a gland opening from which liquid is ejected. The flanges are curved and grooved in such a way that fluid emerging from the gland openings is bent sharply to follow the curvature of the flanges, and thus their ejections are anteriorly aimed, as shown in Fig. 4.

2.6. Other Applications

In addition to the more obvious engineering applications described in the previous sections, the Coanda effect has been very successfully employed in many other areas, including rain and storm water filtration. In such systems, the removal of a significant volume of water via a conduit, such as a downspout or a curbside runoff, is the primary goal. However, the water often contains dirt, grit, leaves, and other types of debris that can accumulate within the conduits, reducing the throughput and ultimately rendering them ineffective. Many of the solutions involve using the Coanda effect to separate the water from the debris (as shown in Fig. 5), since it is only the water that is susceptible to redirection.[44–47] A related application of the Coanda effect has been sewage treatment.[48] To increase the operating reliability of wastewater (sewage) treatment plants, it is necessary to separate the grit transported with the wastewater and other mineral materials from the digestible, organic material. Whilst as much of the mineral matter as possible should be removed, the maximum feasible organic matter should remain in the wastewater. Grit is traditionally separated either by gravity sedimentation or centrifugal force, with the contaminated grit being disposed of, at great expense, considerable inconvenience, and a squandering of natural resources. However, a method has recently been developed whereby the solids in the flow are separated from the wastewater via the flow redirection associated with the Coanda effect.[48] The grit is then washed so that additional attached organic matter is separated from the mineral grit particles, and the clean grit is statically dewatered prior to reuse.

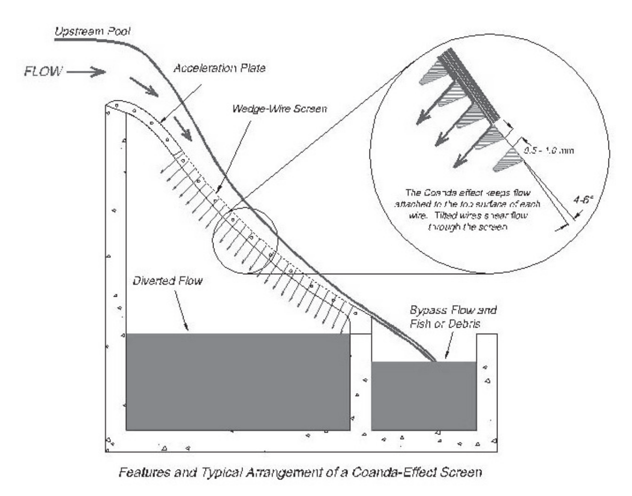


Figure 5. Operating principles of a Coanda stormwater filtration screen. *(Image taken from Wahl, Tony L., 2003,Design Guidance for Coanda-Effect Screens. U.S. Dept. of the Interior, Bureau of Reclamation, Research Report R-03-03. July 2003. [online paper]).*

An alternative utilization of the Coanda principle is to washing and drying processes. In manufacturing processes which require high levels of cleanliness (e.g., semiconductor wafers), it is imperative to clean and dry the robotic devices used. For example, during the wet processing of wafer substrates, robotic end effectors carry the substrates between chemical processing steps, rinse steps, and/or drying steps. Between these steps, it is imperative to clean the end effectors so that substances that adhere to them during transport are not transferred back onto the wafers when they are subsequently retrieved by the same end effectors. In other contexts, the periodic washing and drying of end effectors may be important in terms of minimizing the particle contamination between them and the wafers. Talley and Atkins outline one such cleaning/drying tool for robotic end effectors based on the Coanda principle that minimizes process time, process fluid consumption, and footprint size.[49] On a totally different scale, the dryers used in automatic motor vehicle washing and drying systems typically include one or more nozzles which may be stationary or oscillatory. If they oscillate, they typically do so over a wide angular range so that water will be pushed towards the centre of the vehicle and then down the front and rear. Jones invented a dryer comprising three downwardly-facing overhead nozzles that oscillate in a synchronized manner with the two side nozzles oscillating over a limited range—one on the passenger side and the other on the driver side.[50] A center nozzle located between them oscillates over a wider range, thereby taking advantage of the Coanda effect to drive water on the upper surface of the vehicle toward the side nozzles, which then drive the water along the contours of the vehicle surface and down the sides of the vehicle.

Highway tunnels are often ventilated through a series of air ducts. However, a simpler method employs a jet ejector system blowing longitudinally through the tunnel itself, generally in the direction of the traffic flow. If there is a strong head wind it may also be necessary to ventilate with the wind direction and for this reason, each tunnel is additionally equipped with a second ejector system. Etkin et al. proposed a method for eliminating one of these ventilating fan units by using the Coanda effect to deflect the primary air (jet) sheet in the appropriate direction for a given set of conditions.[51] Two Coanda surfaces are employed adjacent to a nozzle which swivels. By aligning the nozzle with one or the other surface, the ventilating flow can be directed in whichever is the direction of least resistance. As an additional benefit, these Coanda deflected sheets promote enhanced mixing of the jet with the ambient air, compared with conventional fan units. Related experimental work on the vehicular tunnel under the Welland Canal, Canada, (between Lake Ontario and Lake Erie) indicates that "...the utilization of the Coanda effect for jet pump ventilating is workable and attractive."[52] Still other applications of the Coanda effect include the coating of surfaces with powdered materials,[53] the development of drag reduction spoilers for Heavy Goods Vehicles (HGVs)[54], and anti-splash urinals.[55]

3. AEROACOUSTICS AND THE COANDA EFFECT

A wide variety of aeronautical and aerospace applications utilize the Coanda effect, or aspire to, due to the enhanced turbulence levels and entrainment that devices employing this effect generally offer when compared with conventional jet flows. However, such advantages are not usually achieved without a substantial increase in the corresponding acoustic radiation. This obviously detrimental side-effect has meant that in many cases the potential benefits of the Coanda effect have yet to be fully realized. For example, in the petroleum industry, situations often occur in which it is desirable to dispose of a large amount of gas, as quickly and efficiently as possible. This is done by burning off the gas in a process known as flaring. Initially, so-called pipe-flares were used. However, the requirement of certain features (e.g., smokeless combustion over a wide range of gas flows and conditions, reliability of flare ignition by external pilots, and flame stability), soon led to the development of other types of flare. A crucial step in this development was the application of a simple, but effective principle known as the Coanda Effect, to flare design. Figure 6 shows such a flare in operation, and Figure 7 shows the flow field and combustion zone of a typical Coanda flare developed by B.P., known as the Indair. The capacity to entrain large amounts of air means that flares employing the Coanda effect can offer advantages such as smokeless combustion, increased combustion efficiency, and decreased thermal radiation, compared to other types of flare.[56–59]

Coanda flares are also a significant improvement on other flares in terms of pollutant and noise emission. However, despite this improvement, Coanda flares are still a source of considerable noise. Noise pollution has long been recognized as detrimental, in terms of both health and efficiency, to industrial workers, and nowadays noise pollution is regarded as important an industrial hazard as air pollution. Consequently, legislation exists to control the level of noise to which industrial workers can be exposed. Although this has led to much research on various types of noise emitted by industrial machinery, relatively little work has been conducted on noise emission due to the Coanda effect. Indeed, the majority of such research has focused on use of a shield or shroud to deflect the noise.[60] Carpenter and Green performed one of the

Figure 6. An operating I33 Indair waste-gas flare.

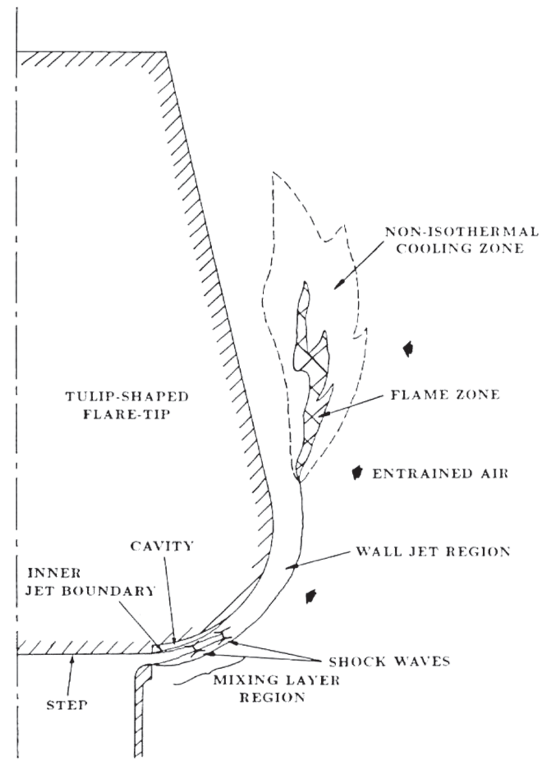


Figure 7. The overall flow field and combustion zone of an Indair waste-gas flare.

first exhaustive studies of the noise sources in external Coanda gas flares.[61] In their work, they identified the fundamental high-frequency noise generating mechanisms associated with Coanda flows as Turbulent Mixing Noise (TMN) and shock-associated noise (SAN). They studied these and other noise mechanisms via scale-model I4 flares of the full-size Indair (I33) flares operated by B.P., with and without a step at the nozzle exit. In a related approach, in which the aim is to understand the fundamental noise-generating mechanisms associated with TMN, Lubert has developed a theory for predicting the TMN emitted by unit volume of jet-type, shear-layer turbulence close to a rigid plane, and extended it to a plane two-dimensional wall-jet.[59,62–65] The improved understanding offered by the development of a model for predicting the noise emitted by three-dimensional flows over Coanda surfaces has allowed investigation of the effect of various flow parameters on the associated acoustic emission and has indicated ways in which the perceived noise levels associated with such external-Coanda flows could be reduced or attenuated.

Lubert's theory is based on Lighthill's acoustic analogy which draws a parallel between the equation of sound in a stationary medium and a wave equation derived from the exact equations of fluid motion to show that TMN can be modeled by a stationary distribution of high-frequency acoustic quadrupoles.[66] This theory was applied to unit volume of free field turbulence, and Ribner's method was used to specify the exact combination of acoustic quadrupoles that should be used.[67] The theories of Curle and Powell were extended to take into account the presence of the rigid plane by developing a "Method of Images" approach (in which each original acoustic quadrupole is replaced by a quadrupole system comprising the original quadrupole plus an "image quadrupole" representing the image of the original in the plane rigid boundary).[68,69] In this way, predictions were made of some of the basic aeroacoustic characteristics associated with a plane two-dimensional wall-jet.[63] Subsequent work by Davies on high-frequency acoustic quadrupoles in close proximity to a rigid sphere indicated that, provided the sources are close enough to the surface, the surface can be regarded as locally plane, since only a small additional component is introduced as a result of the curvature of the surface curvature.[70] Thus, the theory developed for a plane two-dimensional wall-jet was extended to the case of a three-dimensional flow over a rigid Coanda surface. It was found that the relatively simple "Randomly Orientated Longitudinal Quadrupole" (ROLQ) method of modeling the acoustic sources gives reasonable agreement with the results obtained by Ribner's[71] much more complicated source modeling method.[59,62–65] Using these ROLQ sources, the sound emitted by each radial "slice" of a jet was calculated by assuming that the zone of peak turbulence dominates the sound generation within that slice, calculating the sound field radiated by unit volume of turbulence at that location, and then adjusting for the area of the slice. Predictions of the aeroacoustic characteristics associated with the mixing layer region of a three-dimensional turbulent wall-jet were first developed for an observer horizontal to the jet. These were then extended to the case of an observer at some non-zero angle to the horizon. The model was further extended to account for the transition and fully-developed regions of the wall-jet, and finally a method for predicting the aeroacoustic behavior of a three-dimensional turbulent flow over a Coanda surface, was developed.64-65

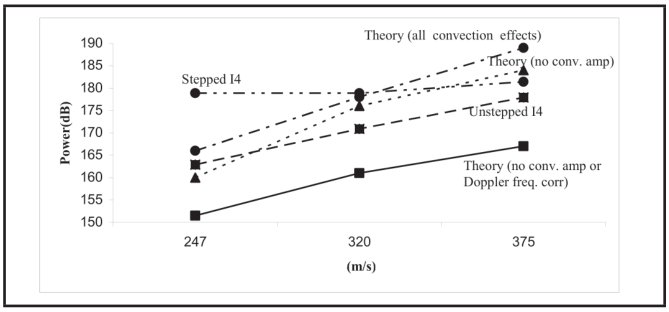


Figure 8. omparison of theoretical predictions with experimental results for the total power emission of a Coanda wall jet to a horizontal observer with slot width. (jet exit velocity, U_{jx} = 320 m/s).

A comparison of the current results with existing theoretical models and experimental data is shown in Fig. 8. The theory is currently being generalized to more commonly-occurring Coanda surfaces, and a theory is also being developed to account for SAN.

4. CONCLUSIONS

The Coanda effect was discovered over 100 years ago, but over the last twenty-five years, the range of applications has grown exponentially. The effect offers significant advantages in terms of substantial flow deflection and enhanced turbulence and entrainment levels. However, in many cases, the full potential offered by the principle is yet to be completely realized, in part due to a lack of understanding of some of the fundamental physical characteristics associated with the effect. This paper describes some examples of use of Coanda flows in engineering and nature, and it describes recent attempts to model the difficulties that can occur when the effect is present, including increased noise levels and jet detachment issues.

REFERENCES

[1] Coanda, H. Procede de propulsion dans un fluide, *Brevet Invent, Gr. Cl. 2, no. 762688 Republique Francaise*, (1932).

[2] Reba, I. Applications of the Coanda effect, *Scientific American*, (June 1966).

[3] Keller, J. B. Teapot effect. *J. Applied Physics*, **28**, 859–864, (1957).

[4] Kistler, S. F. and Scriven, L. E. The teapot effect: Sheet-forming flows with deflection, wetting and hysteresis, *J. Fluid Mech.*, **263**, 19–62, (1994).

[5] Duez, C., Ybert, C., Clanet, C., and Bocquet, L. Beating the teapot effect. *Phys. Rev. Lett.*, **104**, (2010).

[6] Howe, M. S. Section 3.7.1 of "Hydrodynamics and Sound" C.U.P., (2006).

[7] Carpenter, P. W. and Green, P. N. The aeroacoustics and aerodynamics of high-speed Coanda devices, Part 1: Conventional arrangement of exit nozzle and slot, *J. Sound and Vibration*, **208**(5), 777–801, (1997).

[8] Wille, R. and Fernholtz, H. Report on the first European Mechanics Colloquium on the Coanda effect, *Journal of Fluid Mechanics*, **23**(4), 801–819, (1965).

[9] Simpson, R. G., Ahmed, N. A., and Archer, R. D. Improvement of a wing's aerodynamic efficiency using Coanda tip jets, *Journal of Aircraft Design*, **37**, No. 1, (2000).

[10] Latigo, B. O. and Pena, S. Design of an elliptical circulation control airfoil, *Journal of Engineering Technology*, **10**, 33–36, (1993).

[11] Wong, C. and Kontis, K. Pneumatic Flow control studies using steady blowing on a supercritical aerofoil, *Aeronautical J.*, **113**(1139), 53–63, (2009).

[12] Cook, M. V., Buonanno, A., and Erbsloh, S. D. A circulation control actuator for flapless flight control, *Aeronautical J.*, **112**(1134), 48–489, (2008).

[13] Buseman, A. Schuberhohung durch Luftbeimischung (Increasing Thrust by the Addition of Air and Mixing), *Lilienthal Ges. Luftfahrt Bericht*, **118**, (1939).

[14] Li, P. and Halliwell, N. A. Industrial jet noise: Coanda nozzles. *J. Sound Vib.*, **99**, 475–491, (1985)

[15] Bevilaqua, P. M. and Lee, J. D. Design of a Supersonic Coanda Jet Nozzle, AIAA paper, AIAA-84-0333, AIAA 22nd Aerospace Science Meeting, Reno, NV, (1984).

[16] Cornelius, K. C. and Lucius, G. A. Physics of Coanda jet detachment at high-pressure ratio, *Journal of Aircraft*, **31**(3), 591–596, (1994).

[17] Sawada, K. and Asami, K. Numerical study on the under-expanded Coanda jet, *Journal of Aircraft*, **34**(5), 641–647, (1997).

[18] Wing, D. J. Static Investigation of Two Fluidic Thrust-Vectoring Concepts on a Two-Dimensional Convergent-Divergent Nozzle, NASA Technical Memorandum 4574, (December 1994).

[19] Yagle, P. J., Miller, D. N., Ginn, K. B., and Hamstra J. W. Demonstration of fluidic throat skewing for thrust vectoring in structurally fixed nozzles, *Journal of Engineering for Gas Turbines and Power*, **123**(3), 502–508, (2001).

[20] Teodorescu-Tintea, C. Contribution a l'etude de l'effet Coanda et de ces applications pratiques, Dissertation l'Institute Polytechnique de Bucarest, (1962).

[21] Teodorescu-Tintea, C. Recherches sur le reversement de la traction des moteurs turboreacteurs a l'aide de l'effet Coanda, *Rev. Transp. 9, Bucarest*, (1960).

[22] Teodorescu-Tintea, C. Sur l'ecoulement des jets plans dans le voisinage de parois solides au profil divergent; l'effet Coanda, *Rev. Roum. Sci. Techn. Mech Appl. 3, Ed. De l'Academe de RPR Bucharest*, (1964).

[23] Teodorescu-Tintea, C. On a new functional principle in the theory of gas turbines based on the Coanda effect: The turbine fitted with depressive blades, *Rev. Roum. Sci. Tech. Mech. Appl.*, **12**(1), 85–101, (1967).

[24] Perrig, A., Avellan, F., Kueny, J-L., Farhat, M. and Parkinson, E. Flow in a Pelton turbine bucket: numerical and experimental investigations, *J. Fluids Engineering*, **128**, 350–358, (March 2006).

[25] Schuh, H. and Person, B. Heat transfer on circular cylinders exposed to free jet flow, *Int. J. Heat & Mass Transfer*, **7**, 1257, (1964).

[26] Klein, E. Umstromung einer konvexen Kontur durch einen dunnen Flussigkeitsfilm mit freier Oberflache (Adhesion to a convex contour by a thin liquid film with a free surface), *Bericht der DVLR*, (1965).

[27] Lee, D., Hwang, J., Kwon, Y., Kwon, S., Kim, G., and Lee, D. A study on the air knife flow with Coanda effect, *J. Mechanical Science and Technology*, **21**(12), 2214–2220, (2007).

[28] Zanchetta, M., Rigatelli, G., and Ho, S. Y. A mystery featuring right-to-left shunting despite normal intracardiac pressure, **128**, 998–1002, Chest, (2005).

[29] Ashrafian, H., The Coanda effect and preferential right atrial streaming, **130**(1), 300, Chest, (2006).

[30] Guntheroth, W. and Miyaki-Hull C. Coanda effect on ductal flow in the pulmonary artery, *J. Ultrasound in Medicine*, **18**(3), 203–206, (1999).

[31] Shiota, T., Jones, M., Teien, D., Yamada, I., Passafini, A., Knudson, O., and Sahn, D. J. Color doppler regurgitant jet area for evaluating eccentric mitral regurgitation: An animal study with quantified mitral regurgitation, *J. Am. Coll. Cardiol.*, **24**, 813–819, (1994).

[32] Ginghina, C., The Coanda effect in cardiology, *Journal of Cardiovascular Medicine*, **8**(6), 411–413, (2007).

[33] Jackson, R. R. Self-Inflating Endotracheal Tube (U. S. Patent 3707151), (1971).

[34] Baumont, G. Static Respirator for Artificial Respiration (U.S. Patent 3815593), (1971).

[35] Phuc, T.N. High-Frequency Artificial Respirator (US Patent 4788974), (1988).

[36] Qudaisat, I. Y. Coanda effect as an explanation for unequal ventilation of the lungs in an intubated patient?, *British Journal of Anaesthesia*, **100**(6), 859–860, (2008).

[37] English, J. The Coanda effect in maritime technology, The Naval Architect, (April 1999).

[38] Haynes, H.W. Chambered anti-Coanda jet marine propulsion device with gaseous boundary layer for a thrust jet flow stream exhibiting staged controlled boundary layer separation properties, vessel trim adjustment, and movable thrust vector application points(s) (U.S. Patent 5545063), (1993).

[39] Howe, M. S. Noise generated by a Coanda wall jet circulation control device. *J. Sound Vib.*, **249**, 679–700, (2002).

[40] Beese, J., Peters, R., and Wade, M. An improved propulsion system for marine vehicles, OCEANS 1984, **6**(1), 328–336, (1974).

[41] Split-Cycle Technology Ltd., accessed March 2011, retrieved from *http://www.linux-host.org/energy/acoanda.html*, (2001).

[42] Giles, B.D. Fluidics, the Coanda effect, and some orographic winds, *Arch. Met. Geoph. Biokl.*, Ser. A, **25**, 273–279, (1977).

[43] Eisner, T. and Aneshansley, D. J. Spray aiming in bombardier beetles: Jet deflection by the Coanda effect, *Science*, **215**, 4528, 83–85, (January 1982).

[44] Fox, S. P. Leaf Guard for Gutters (US Patent 6904718), (2004).

[45] LeavesOut Gutter Covers, accessed March 2011, retrieved from *http://www.hunters3service.com/leavesout.htm*, (2010).

[46] Esmond, S. E., Quinn, L., and Weir, R. K. Rain and storm water filtration systems (U.S. Patent 6705049), (2004).

[47] Coanda Inc., accessed March 2011, retrieved from *http://www.coanda.com/default.htm*

[48] Huber Technology, Inc., accessed March 2011, retrieved from *http://www.huber-technology.com/huber-report/ablage-berichte/grit-separation-and-treatment/1000-coanda-grit-washing-plant-installations.html?L=0*

[49] Talley, J. R. and Atkins, W. L. Method and Apparatus for Washing and/or Drying Using a Revolved Coanda Profile (U.S. Patent 6730177), (2004).

[50] Jones, A. Motor Vehicle Dryer with Coanda Effect Drying (U.S.Patent 574916), (1996).

[51] Etkin, B. Korbacher, G. K., Nishimura, Y., Ribner, H. S., and Wilson, A.E. Application of an ejector nozzle and Coanda surface to ventilation of a highway tunnel, *UTIA technical note* 82, (1964).

[52] Nishimura, Y. Application of a jet pump and Coanda surface to ventilation of a highway tunnel, *UTIAS technical note* 82, (1965).

[53] Horii, K. and Sawazaki, H. Method for coating surfaces of a powdered material by directing coating material into Coanda spiral flow of powdered material (U.S. Patent 5188868), (1993).

[54] The Coanda effect, *Meridian International Research*, accessed March 2011, retrieved from *http://www.meridian-int-res.com/Aeronautics/Coanda.htm*, (2005).

[55] Rice, J. J., Yavas, M. and Helbig, T. Anti-Splash Urinals (U.S. Patent Appl. No,. 12/455,959), (2010).

[56] Desty, D. H. No smoke without fire, *Proceedings of the Institution of Mechanical Engineers*, **197A**, 159–170, (1983).

[57] Desty, D. H, Boden, J. C., and Witheridge, R. E. The origination, development and application of novel premixed flare burners employing the Coanda effect, 85th Nat. AIChE meeting, Philadelphia, (1978).

[58] Jenkins, B. G., Moles, F. D., Desty, D. H., Boden, J. C., and Pratley, G. The aerodynamic modelling of flares, Energy Technology Conference and Exhibition, New Orleans, ASME Paper 80-Pet-86, (1980).

[59] Parsons, C. An experimental and theoretical study of the aeroacoustics of external-Coanda gas flares, PhD Thesis, University of Exeter, (1988).

[60] McMurray, R. and Pratley, G. Flare having noise attenuation (US Patent 4486167), (1984).

[61] Carpenter, P. W. and Green, P. N. Noise sources in external Coanda-type gas flares, AIAA Paper 83-0758, (1983).

[62] Parsons, C. and Carpenter, P. W. The noise emitted by turbulent jets in close proximity to solid surfaces, AIAA Paper 86-1869, Seattle, USA, (1986).

[63] Smith, C. and Carpenter, P. W. The effect of solid surfaces on turbulent jet noise, *J. Sound and Vibration*, **185**(3), 397–413, (1995).

[64] Carpenter, P. W. and Smith, C. The aeroacoustics and aerodynamics of high-speed Coanda devices, Part 2: Effects of modifications for flow control and noise reduction, *J. Sound and Vibration*, **208**(5), 803–822, (1997).

[65] Lubert, C. P. Application of turbulent mixing noise theory to flows over Coanda surfaces, *Int. J. Acoustics & Vibration*, **13**(1), 17–30, (2008).

[66] Lighthill, M. J. On sound generated aerodynamically. I. General Theory, *Proc. Roy. Soc.*, **211**, 564–587, (1952).

[67] Ribner, H. S. Quadrupole correlations governing the pattern of jet noise, *J. Fluid Mech.*, **38**, 1–24, (1969).

[68] Curle, N. The influence of solid boundaries upon aerodynamic sound, *Proc. Royal Soc.*, **A231**, 505–514, (1955).

[69] Powell, A. Aerodynamic noise and the plane boundary, *J. Acoust. Soc. America*, **32**, 982–990, (1960).

[70] Davies, H. G. The radiated fields of multiple point sources near a solid spherical surface, *J. Fluid Mech.*, **43**, 597–606, (1970).

[71] Ribner, H. S. The generation of sound by turbulent jets, *Adv. in App. Mech.*, **VIII**, 103–182, (1964).