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1pNS9. On Some Recent Applications of the Coanda Effect to Acoustics

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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, medicine, 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, a considerable increase in associated noise levels etc. In many cases, 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 noise levels.

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1. The Coanda Effect

The Coanda effect was a phenomenon 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, and deduced that the attachment was produced by a decrease in surface pressure in the separation bubble which he observed to form just downstream of 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^o. 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". The jet is pulled onto the curved surface as a result of the low pressure region which develops as entrainment of the ambient air by the jet removes air from the region between the jet and the surface. The balance between the inward radial pressure gradient (suction force) and the outward centrifugal (inertia) force then holds the jet to the wall. The effect of this longitudinal curvature is to cause increased entrainment and jet growth. In some cases, jets entrain up to twenty times their own volume whilst following the curved surface[3]. As a consequence of the enhanced turbulent levels and entrainment associated with the Coanda effect, compared with conventional jet flows, there are numerous man-made and natural examples to be found[4].

The most serious problem in the application of the Coanda effect is jet flow detachment[5]. If shock waves are formed inside the jet plume, jet flow detachment from the solid surface occurs because of shock wave - boundary layer interaction However, there are methods for delaying or preventing this detachment, or breakaway. Since it is a result of a high static pressure at the nozzle exit, one way of slowing it is by lowering the exhaust static pressure. Thus it can be delayed considerably by the use of a convergent-divergent nozzle, for example[5].

2. Applications of the Coanda Effect

Some of the most significant applications of the Coanda principle will be discussed here, including in aerodynamics, industry, medicine, maritime technology, the natural world and aeroacoustics. The recent utilization of the Coanda effect in other, novel applications will also be presented.

2.1 Aerodynamics

As one of the most efficient methods of generating increased lift, the Coanda effect has many aerodynamic applications. For example, 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 airfoil trailing edge, producing circulation and thus, lift. 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 displacement depends entirely on the momentum of the blowing jet. Simpson[6] , Latigo[7] and others have confirmed such circulation control wings (CCW) to be effective in offering significant lift enhancement compared with conventional airfoils although a major disadvantage of this technique is that it requires additional Auxiliary Power Units (APU's) or engine capacity in order to supply the bleed air for the slot blowing. In related work, Wong & Kontis[8] reported that an aerofoil with a Coanda trailing edge showed improved stability at the edge of the wake, and Cook *et al* [9] described a flow control actuator using a moveable Coanda surface which allows the formation of upper and lower slots, giving bidirectional control rather than the usual unidirectional control offered by the typical (single) fixed slot. Thus the trailing edge blowing over a Coanda surface yields a circulation control device for increasing the lift of an aircraft wing, which offers the same control as a device with a conventional flap, without the flap (ie flapless!).

The Coanda principle can also be applied to thrust vectoring, which 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), and enables aircraft to perform various maneuvers that would not be possible otherwise. The principle of thrust augmentation due to the increased mixing associated with the Coanda effect is well understood, and has been discussed by Busemann[10], amongst others. Supersonic jets, such as those used in aircraft, present an additional problem. Such jets contain a system of shock waves inside the jet plume. The interaction of the jet with these shock waves can act to precipitate jet flow detachment from the solid surface occurring. Bevilaqua *et al*[11] performed one of the few supersonic Coanda jet studies in which 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. Cornelius and Lucius[12] subsequently performed an experimental study of a two dimensional underexpanded supersonic Coanda jet flow around a circular cylinder. They confirmed the work of Bevilaqua, determining that jet flow detachment could be significantly delayed by employing a convergent-divergent nozzle. In related work, Sawada and Asami[13] performed a numerical study on an underexpanded supersonic Coanda jet flowing around a circular cylinder.

Wing[14] used a conventional two-dimensional convergent-divergent nozzle and conducted a static investigation of two thrust vectoring concepts, one of which utilized the Coanda principle. This concept was 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 proved 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. Wing postulated that the high aspect ratio of the nozzle may have impeded the effectiveness of the thrust vectoring concept.

The Coanda effect has been used in aircraft design since the mid 1950's. One of the most recent applications has been to the B-2 Spirit "stealth bomber" (see Figure 1), an aircraft specifically designed to employ stealth technology to penetrate anti-aircraft defenses. The

B-2 exhaust system exploits the Coanda principle in the exhaust ducts which have curved profiles that flatten out to wide slits and open out into over-wing trenches. The Coanda effect is used to direct the thrust aft (towards the rear) whilst simultaneously concealing the nozzle openings from direct rear view.

Figure 1: The B-2 Stealth Bomber
(Source: http://www.math.tau.ac.il/~turkel/stealth.jpg)

2.2 Industry

The primary areas where the Coanda principle has been used to great effect in industrial applications are in reaction turbines, swirl atomizers and galvanizing techniques, cooling of cylinders and fluid logic devices.

Reaction turbines develop torque by reacting to the gas or fluid's pressure or mass. In a new kind of reaction turbine[16-19] the fluid, combustion gas or hot air is discharged through nozzles on a rotating hollow shaft. It is then deflected along adjoining backward curving 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 allows the concave surface to cool.

The cooling of circular cylinders is usually achieved by placing the cylinders in an unlimited uniform parallel air stream, with negligible turbulence in the main stream. Improved cooling[20] can be achieved by locating the cylinder symmetrically in a two-dimensional finite-width jet. 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 (such as that shown in Figure 2) 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. With a sharp-edged lip the atomization is found to be poor, but when a curved lip is used Klein[21] reported that the Coanda effect ensures good atomization. In a related problem, Lee *et al*[22] 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. 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 Coanda effect as it leaves the nozzle, causing the potential splashing region to be moved further downstream.

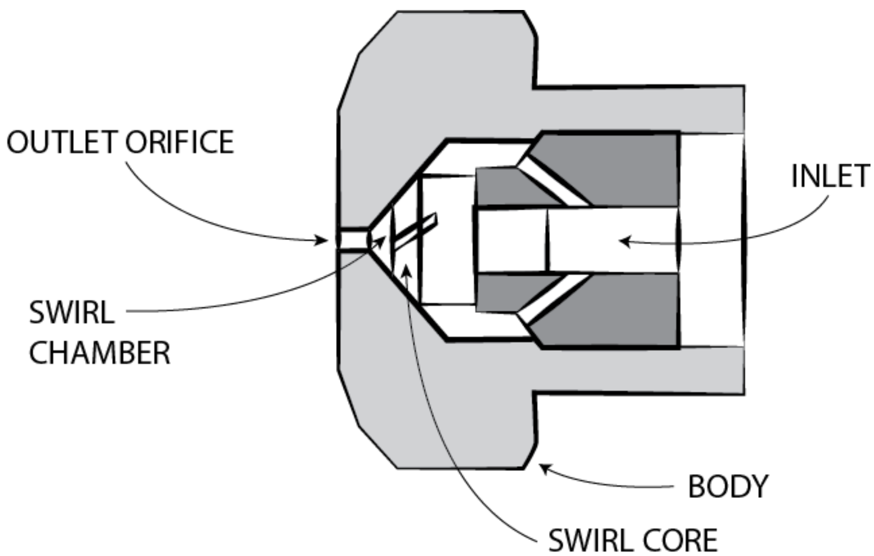

Figure 2: A typical swirl atomizer (Source: http://commons.wikimedia.org/wiki/File:Swirl_nozzle.png)

2.3 Medicine

The Coanda effect is an established physical phenomenon of fluid flow which occurs in several areas of medicine. One such area is cardiology. In a normal heart there is a ductal jet close to the left pulmonary artery. During right ventricular ejection, the ductal jet adheres to the left wall of the main pulmonary artery. Pulmonary atresia is an extremely rare form of congenital heart disease in which the pulmonary valve does not form properly. This valve is a flap-like opening on the right side of the heart that allows blood to move to the lungs. When a person has pulmonary atresia, a solid sheet of tissue forms where the valve opening should be and right ventricular ejection is absent. Because of this defect, blood from the right side of the heart cannot go to the lungs to pick up oxygen. According to Guntheroth & Miyaki-Hull[23] the Coanda effect causes the ductal jet to stream down the right wall of the pulmonary artery to the pulmonary valve, reverse, and maintain a parallel column back toward the bifurcation. If this reversed flow is mistaken for ejection from the right ventricle, the diagnosis of pulmonary atresia may be missed.

Color Doppler flow mapping is an imaging technique that is widely used in clinical applications. Since it provides visualization of valvular regurgitations and other abnormal flows it is commonly used in assessing the severity of such lesions. However, Ginghina[24] argues that the Coanda effect may alter the interpretation of color Doppler images, by influencing jet size and color encoding, leading to smaller Doppler jet areas, greater variance and reverse velocity encoding. Ginghina warns that this effect should be accounted for in order to perform "…an appropriate echocardiography assessment of valvular regurgitation and other abnormal flows".

Artificial respiration is the act of simulating respiration, which provides for the overall exchange of gases in the body by pulmonary ventilation, external respiration and internal respiration. An endotracheal tube (such as that shown in Figure 3) is used for airway management, mechanical ventilation and as an alternative route for many drugs if an intravenous (IV) line cannot be established. The tube is inserted into a patient's trachea in order to ensure that the airway is not closed off and that air is able to reach the lungs. However, serious damage can occur to the tracheal mucosa as a result of the pressure of the cuffs in the ventilating tubes. Jackson[25] suggested an endotracheal tube with a self-inflating cuff in which "...the Coanda effect, by which a laminar flow stream of air tends to hug and follow the direction of a surface, may be employed advantageously to guide air into the cuff for inflation purposes."

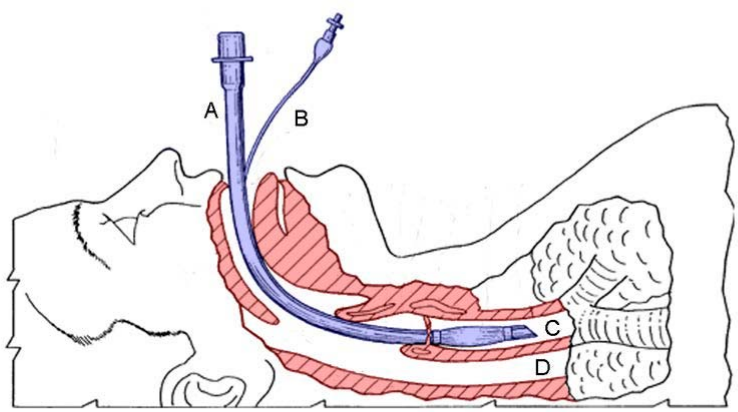

Figure 3: The Coanda effect in Artificial Respiration -- A: endotracheal tube, B: cuff inflation tube with pilot balloon, C: trachea, D:esophagus (Source: http://commons.wikimedia.org/wiki/File:Endotracheal_tube_colored.png)

A fluid logic device is an all-fluid system which uses the principle that a free jet flowing in a diverging channel can attach itself to either wall, and that it can be forced to separate from one wall and attach instead to the other via the Coanda effect (it effectively changes the low pressure area to one of relatively high pressure) using small auxiliary jets flowing through holes in the walls. This ability to provide control using the Coanda effect rather than using mechanical parts offers tremendous potential in a medical environment. Baumont[26] developed a static respirator for artificial respiration which uses two miniature pneumatic units made mainly of ceramic glass (a monostable fluid amplifier and a bistable fluid amplifier). More recently, Phuc[27] invented a high-efficiency and compact high-frequency artificial respirator comprising fluidic control devices utilizing the Coanda effect, such as those described previously.

However although the Coanda principle offers many benefits in medical applications, as stated earlier, it is important to be aware that in some cases it may be potentially detrimental. For example[28] unequal inflation of the lungs during artificial ventilation of a paralyzed and intubated patient using a single-lumen tracheal tube can result from the Coanda effect occurring in the trachea. Misdiagnosis of cardiac irregularities due to the appearance of potentially misleading phenomena resulting from the Coanda principle must also be guarded against.

2.4 Maritime Technology

There are numerous occasions in marine engineering where the Coanda effect can be used to enhance performance, particularly in low-speed ship manoeuvring and dynamic positioning. However, there are also many examples of it being experienced by floating or submerged vessels when, according to English[29],"…its presence usually detracts from performance".

Vessel propulsion is one example of where the Coanda principle can have a negative impact. For example, Haynes[30] describes a marine propulsion system for use on vehicles which must perform well at both low and high speeds. Such systems often experience boundary layer Coanda effect problems. In order to try to mitigate such Coanda-induced thrust losses, Haynes suggests an anti-Coanda method 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. Another similar problem[29] occurs when a ship is being handled at low speed. In this case when trying to go astern the non-symmetric flow and pressure on the hull can cause the Coanda effect to produce a turning moment on the ship that may not be predictable. As the ship's speed increases the effect reduces due to the lower entrainment observed when the Coanda effect occurs in a co-flowing stream.

Underwater exploration has hitherto been hampered by the difficulties of propelling a submerged hull efficiently and economically, due to fluid resistance. However, Beese et al[31] describe the design and testing of a submersible vehicle (the 'Hydropod') that uses the Coanda effect to reduce the fluid resistance on its hull. A peripheral nozzle at the front of this aerodynamically shaped submersible ejects fluid and the Coanda effect causes this jet to attach to and envelope the body, simultaneously reducing the fluid resistance to its hull and generating a forward thrust via mass transfer. Tests indicate that submersible devices incorporating the Coanda effect have advantages over existing methods of propulsion in manoeuvrability and in the reduction of drag.

Additionally, semi-submersible designs with underslung azimuthing thrusters can suffer from interaction problems between the jet-effluxes (slipstreams or thruster washes) and the vessel structure unless steps are taken to avoid or control them. English[29] reports that "…several instances of the Coanda effect have been observed in the course of experimenting with models of ships and semi-submersibles…" and he postulates that similar effects would be observed on full size ships, noting that steps such as fitting an anti-Coanda plate (to limit slipstream impingement) should be taken.

According to the results of physical modeling by English[29], "…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…". 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.

2.5 The Natural World

In addition to more obvious engineering applications, many examples of the Coanda principle have been found in the natural world. For example, Eisner and Aneshansley[32] report that Bombardier beetles eject a defensive fluid (a hot quinine-containing secretion) when disturbed, and rely on the Coanda effect for aiming, as shown in Figure 4.

Figure 4: The Bombardier Beetle and the Coanda Effect (Image reproduced by kind permission of Thomas Eisner & Daniel Aneshansley, Cornell University).

In another application, there are multiple instances in which the principles of fluidics applies to topographically directed winds[33]. For example, in the Moldavian Plateau in Romania (Figure 5) an arc is formed by the Carpathian and Transylvanian Alps and the Coanda effect causes northerly air streams traveling around this arc to be diverted towards the Southwest (with an associated low pressure area further to the southwest). This effect, together with the fohn 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. A similar effect is observed in Big Delta, Alaska, U.S.A. where 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. The behavior of the Rhone Valley Mistral in France can also be explained by the Coanda effect. The mistral blows along the curved east side of the Rhone delta, changing direction unexpectedly from northerly to north-northwest as it hugs the Alps.

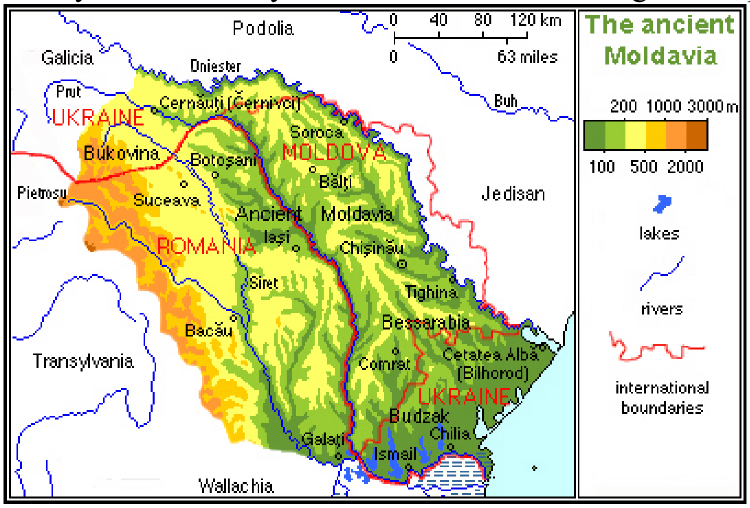

Figure 5: The Moldavian Plateau Microclimate
(Source: http://en.wikipedia.org/wiki/File:PhysicalAncientMoldavia.jpg)

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 which can accumulate within the conduits reducing the throughput and ultimately rendering them ineffective. Thus, a great deal of effort has been directed at this problem. Many of the solutions involve using the Coanda effect to separate the water from the debris (as shown in Figure 6) since it is only the former that is susceptible to redirection[34-35].

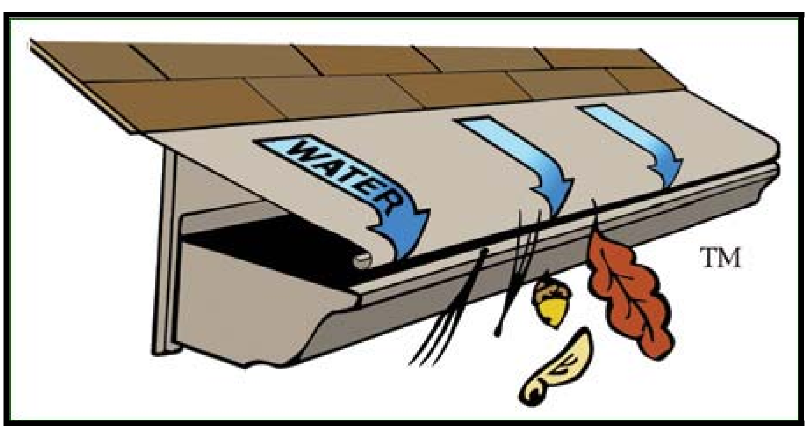

Figure 6: Stormwater filtration (Source: http://www.leavesout.com/compare_leavesout_gutter_guards.php)

The more general problem of storm water filtration has been addressed, amongst others, by Esmond *et al*[36] who suggest that a curbside inlet to a storm drain is fitted with a Coanda screen mounted between a raw inlet basin and an outlet basin. Filtered water is allowed to pass over the screen and fall through it into the outlet basin, then flowing onward via an outlet pipe. Captured debris and waste fall into a retention basket which can then be lifted out of the curbside inlet and emptied when it is full. Other practical ways to clean up storm water runoff also incorporate the Coanda effect, such as a downspout wire filter developed by Coanda Inc.[37].

Another successful application of the Coanda effect has been to sewage treatment [38]. To increase the operating reliability of wastewater 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 either separated by gravity sedimentation (grit channels) or centrifugal force (circular and vortex grit traps) with the contaminated sewage treatment plant grit being disposed of, at great expense, considerable inconvenience and a squandering of natural resources. However, a method utilizing the Coanda principle has recently been developed[38] whereby the grit can now be washed and reused, for example for road bedding. The solids in the flow – primarily grit particles and organic matter – are separated from the wastewater via flow reduction associated with the Coanda effect. 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.

An alternative utilization of the Coanda principle is to washing and drying processes. In manufacturing processes which require high levels of cleanliness (eg. semiconductor wafers) it is necessary to clean and dry the robotic devices used. Talley and Atkins[39] 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.

The dryers used in automatic motor vehicle washing and drying systems typically include one or more nozzles, which may oscillate or they may be stationary. 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[40] invented a dryer comprising three downwardly-facing overhead nozzles. The nozzles 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. A center nozzle, located between the two side nozzles, oscillates over a wider range to take advantage of the Coanda effect to drive water on the upper surface of the vehicle towards the side nozzles, which then drive the water along the contours of the vehicle surface and down the sides of the vehicle.

Conventionally, powdered material such as particles, pellets or fine fibers have had a surface coating (functional or protective) applied by using a mixer with agitating blades or a jet flow. However, these methods are difficult to apply to powdered materials of a micron or submicron order, due to the tendency of a fine material to form an aggregate mass due to secondary coagulation. This mass can then easily break due to forced mechanical mixing. Additionally, the powdered and coating material tend to adhere to the wall of the coating device during the coating process. Horii and Sawazaki[41] describe an attempt to overcome these difficulties by injecting the powdered material into a Coanda spiral flow which is then subjected to the coating material.

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, although such a method can only be applied to relatively short tunnels which have two tubes, each carrying one-way traffic. The ventilation is generally in the direction of the traffic flow, except in circumstances in which there is a strong head wind, in which case it may be necessary to ventilate with the wind direction because short tunnels are sensitive to external wind influence. Consequently such tunnels must be equipped with a second ejector system. Etkin *et al*[42] proposed a method for eliminating one of the fans by using the Coanda effect to deflect the primary air (jet) sheet in the appropriate direction. Nishimura[43] performed related experimental work on the vehicular tunnel under the Welland Canal in Canada (Figure 7), and his results indicated that "…the utilization of the Coanda effect for jet pump ventilating is workable and attractive".

Figure 7: The Welland Canal Tunnel
(source:http://en.wikipedia.org/wiki/Welland_Canal)

Still other applications of the Coanda effect include the development of drag reduction spoilers for Heavy Goods Vehicles (HGV's)[44] and anti-splash urinals[45].

3. Application to Aeroacoustics

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 features such as smokeless combustion over a wide range of gas flows and conditions, reliability of ignition of the flare 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. This capacity to entrain large amounts of air meant 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[46-48]. They are also a significant improvement on other flares in terms of pollutant and noise emission. An operating I33 Coanda waste-gas flare is shown in Figure 8.

Figure 8: An Operating Coanda Flare

Despite the relative improvement the Coanda flares offer in terms of noise pollution, they are still a source of considerable unwanted acoustic radiation. Noise pollution has long been recognized as detrimental, in terms of both health and efficiency, to industrial workers, and nowadays 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 being carried out 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[49] has focused on use of a shield or shroud to deflect the noise. In an alternative approach in which the aim is to understand and alter the fundamental high-frequency noise generating mechanisms associated with Coanda flows, namely Turbulent Mixing Noise (TMN) and Shock-Associated noise (SAN), a theory was developed[50-51] for predicting the TMN emitted by unit volume of jet-type shear-layer turbulence close to a rigid plane, and extended to a plane two-dimensional wall-jet. Since most flows of practical interest are three-dimensional, and often the surface is curved, this model was further extended[52-53] to predict the aeroacoustic characteristics of a three-dimensional turbulent flow over a particular Coanda surface. Comparisons with experimental data were good, and the theory is currently being generalized to more commonly-occurring Coanda surfaces.

4. Conclusions

The Coanda effect was discovered over 100 years ago, but the range of applications continues to grow. 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 describes recent attempts to model the difficulties that can occur, such as increased noise levels and jet detachment issues.

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