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PREVIEW

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Coanda effect jet around a cylinder with an interacting adjacent surface

Churchill, Randolph Allen, Ph.D.

West Virginia University, 1992

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PREVIEW

**Coanda Effect Jet Around A Cylinder With
An Interacting Adjacent Surface**

Submitted to the
College of Engineering
of
West Virginia University
In Partial Fulfillment of Requirements
For The Degree of Doctor of Philosophy

by
Randolph Allen Churchill
Morgantown, West Virginia
1992

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PREVIEW

Abstract

The affects of placing a plane solid surface in close proximity to a Coanda effect jet turning over a cylinder surface are investigated to help judge the possible application of this type of jet to manufacturing line processes. The adjacent surface may represent a moving sheet or conveyor line and the Coanda jet is proposed as a coating control mechanism for fluid coatings on sheets or a particulate removal device. Coating control has traditionally been accomplished with a normal directional air-knife (straight jet). An air-knife strips a fluid film with pressure gradient forces. The Coanda jet develops both shear stress and pressure gradient forces and these two affects together can achieve the desired effect.

A turbulent $k - \epsilon$ finite element model is developed within an accepted commercial analysis software system (FIDAP) and presented that studys the effects of cylinder-sheet separation distance and jet-to-gap angular placement of the jet. It was assumed that the operation was isothermal and that the sheet speed was negligible compared to the air jet speed. Unconstrained jet models were compared with experimental results to validate the modeling method and optimize the empirical constants in the $k - \epsilon$ equations. Acceptable agreement was found if the C_2 parameter in the equations was increased from 1.92 to 3.0.

When this refined method was applied to the situation where a jet is adjacent to a surface it was found, for small gap sizes, that the flow stagnates and recirculates above the gap for jets placed greater than about 150 degrees. Maximum shear stress and pressure gradient values increased exponentially for a decreasing gap size and physical geometric constraints will be the limiting factor to efficiency. For initial jets of similar slot size and velocity this study shows that the Coanda jet develops stripping forces about 1/3 as great as the regular air-knife, but has advantages such as directed flow. The Coanda jet is seen as a viable option to air-knives for certain operations.

Acknowledgments

This project, as most worthwhile ventures, involved its fair share of trials and tribulations and triumphs. I was most fortunate to be surrounded by considerate people who helped ease the burdens either by technical prowess or emotional encouragement; many of these people served wearing both hats. Hopefully they have enjoyed the highlights along the way as I have. It has been my absolute joy to spend the last couple of years rubbing elbows with Robert Craven, Bill Preece, Kurt VanVoorhies, Tom Bonazza, Chris Chaney, Sunil Mathews, Marshala Wright, Ralf Wohl, Kenny Vance, JC Pack, Cliff Judy, Tracy Novak and Ken Craven. Greg Thompson deserves a special attaboy for his steadfastness and perseverance.

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This page cannot possibly conclude without mention being made of the contribution of my folks and the rest of my family. Gil and Lucy Churchill managed to raise four boys (Kent, Alan, Ralph and me) and can be proud of each. For this undertaking of mine they provided a safe retreat with food, comfort, distraction and love. The next family addition, my fiancée Judith Walls, has cared for me, put up with my moods and jumped in to edit documents and make proper sentences from my gibberish. May I always show similar patience during our life together. Lacy Blue deserves a pat on the head as well for sharing my weekend walks and cuddling with me on the couch to relax for a few minutes every day.

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Nomenclature

c	chord
C	representative coefficient in matrix equation
C_1, C_2	empirical constants in k- ϵ model
C_L	lift coefficient = $\frac{L}{1/2 \rho U_\infty^2 c}$
C_p	static pressure coefficient = $\frac{(p-p_\infty)}{1/2 \rho U_\infty^2 C}$
C_μ	blowing-jet momentum coefficient = $\frac{\rho b V_{jet}^2}{1/2 \rho U_\infty^2 C}$; empirical
	constant in k- ϵ model
E	empirical factor in separation criterion or entrainment
F	forcing term in matrix equation
g	gravitational constant
G	heat generation by viscous shear
I_1, I_2, I_3	integral parameters of the velocity profile
k	turbulent kinetic energy
K	curvature correction factor; representative coefficient in matrix equation
L	parameter in Spalding's velocity profile; lift per unit span
L_K	Kolmogorov length scale parameter; characteristic length
M	dimensionless mass flux in wall jet = $\frac{\int_0^\delta \rho u dy}{\rho U_\infty c}$; it can be shown that $M = \frac{\delta I_1 U}{U_\infty c}$
M_{BL}, M_J, M_e	dimensionless mass flux, in upstream boundary layer, from blowing slot, and entrained by wall jet, respectively
n	$1/n$ is exponent in power-law profile used to represent upstream boundary-layer profile
P	static pressure, static pressure in undisturbed free stream, and mean static pressure in curved wall jet
P_{gap}	pressure across the smallest distance between plane and Coanda surfaces
P_{jet}	jet plenum pressure
p_s	pressure in separation bubble at trailing edge
p_s^*	calculated wall-jet separation pressure for any given estimate of C_μ
Q	volume flux in wall jet = $M U_\infty c$
r	radius of curvature of surface
Re	Reynolds number = $\rho U L / \mu$
Ri	Richardson number
t	blowing slot height; time in derivatives
τ_K	Kolmogorov eddy time scale
u	velocity
$\bar{u}$	mean velocity

u'	tangential velocity turbulent perturbation
u^+	Law-of-the-wall non-dimensionalized velocity
U	velocity at outer edge of wall jet; velocity
U_m	peak velocity in jet profile
U_∞	velocity in undisturbed free stream
U'	velocity that would prevail at outer edge of wall jet if stagnation pressure were equal to free-stream stagnation pressure; therefore $U' \equiv U_\infty \sqrt{(1 - C_p \delta)}$
v, v'	normal velocity component, normal direction turbulent perturbation
v_K	Kolmogorov eddy velocity scale
V	velocity at outer edge of upstream boundary-layer profile; velocity
V_{jet}	velocity of blowing jet at slot exit
w	3rd dimensional velocity turbulent perturbation
x, y	coordinates parallel and normal to surface
$y_m, y_{m/2}$	coordinates of points at which $u = U_m$ and $u = 1/2 U_m$, respectively, in wall-jet profile
y^+	non-dimensionalized normal direction distance
Z	parameter in Spalding's velocity profile equation $= (\text{law-of-the-wall vel at outer edge of BL}) / (\text{mainstream velocity})$
β	parameter in Stratford's separation equation
δ	laminar BL thickness, wall jet thickness, fluid film thickness
ε	turbulent energy dissipation
η	Kolmogorov length scale
θ	angular position from slot exit for curved wall jet; also momentum-defect thickness of a shear layer
μ	dynamic viscosity
μ_t	turbulent or apparent viscosity
κ	curvature parameter
ν	kinematic viscosity
ξ	dimensionless distance $= y / \delta$
ρ	fluid density
$\sigma_k, \sigma_\varepsilon$	empirical constants in k- ε model
τ	shear stress
ϕ, φ	local coordinate transformation vectors

Subscripts / Superscripts

a	ambient
A, B	denotes conditions at points A and B
BL	boundary-layer
i	denotes parameters of initial wall-jet profile
i, j	direction in coordinate space
i	derivative w.r.t. i
max	maximum value
$s, surf$	surface
sep	separation
T	transpose
w	denotes parameters at wall/surface
∞	freestream condition
$*$	nondimensionalized value

Introduction

This document presents the concept of a Coanda jet over a cylinder with an adjacent interacting plane surface that may be solid or have a fluid coating attached to it as might be found in many manufacturing processes. The jet interaction with the sheet is as a parallel flow as opposed to the normal direction used by conventional jets (known as air-knives) used for coating thickness or sheet motion control. Traditional coating control methods using air forces aim a high pressure jet of air directly at the sheet. A sharp pressure dome results and the stripping efficiency is proportional to the maximum pressure gradient along the surface of this pressure distribution. The air jet is oriented perpendicular to the surface and does no useful work after the initial impingement. The flow deflects from the surface both above and below the jet and may dangerously spread liquids or particulates in an uncontrolled fashion. Forces on the surface result from the pressure gradients, only as any viscous forces due to flow velocity along the sheet are negligible in comparison.

A Coanda jet coating control device alters the jet flow to spread out the pressure dome and use viscous forces to impact the surface. The concept is illustrated in Fig. 1. The jet flows over the surface of a cylinder placed close to the sheet surface, forming a strong tangential flow through the gap formed between cylinder and sheet surfaces. The jet starts at some angular position away from the gap to allow the jet to grow in size and entrain fluid to increase the impact of the jet flowing through the gap. The jet flows out of this channel or gap and is pulled away from the cylinder as it attaches to the sheet and flows along the sheet; the expanding flow prefers to stay with the flat surface. The dominant interacting force is shear as opposed to the pressure gradient so the magnitude of the force is not as great as air-knife jets but the characteristics of the flow may be useful for certain special applications. The jet flow direction is tightly controlled which is beneficial for processes involving dangerous chemical or high temperature fluids. The jet remains attached to the

sheet for a significant distance—a characteristic which may aid heat transfer applications and particulate removal cases. The jet may use another gas or entrain a particulate stream necessary for processing. These jets may be applicable to several types of manufacturing and processing operations such as sheet coatings, film processing and composite material production.

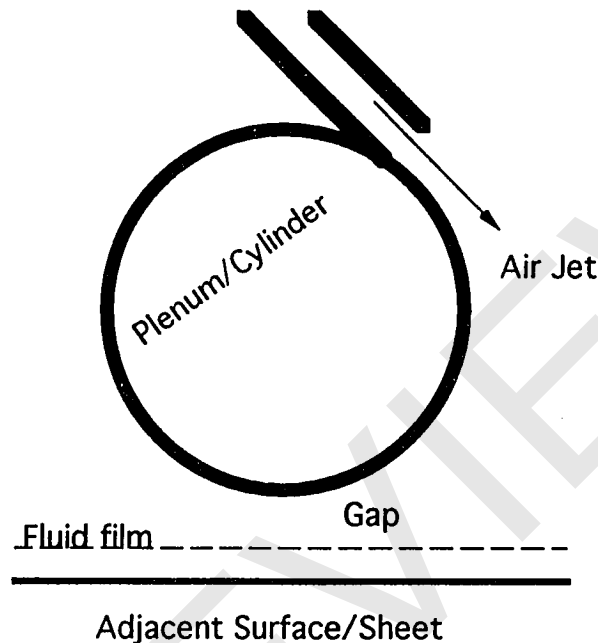


Fig. 1 Coanda jet coating control concept.

A finite element model has been developed in FIDAP, a popular flow simulation and analysis computer software, and refined to simulate the jet interaction with the surface and a test matrix of operating conditions has been run to cover a wide range of possible applications. The examination of gap sizes and jet orientation will enable designers to apply Coanda jets to particular situations. The adjacent surface is taken as stationary because any adjacent surface speed would be negligible compared to the jet speed (on the order of Mach = 0.5). The surface is also taken to be perfectly flat and non-porous as a most general case. The proposed finite element solution scheme is validated by comparing numerical and

experimental results for an unconstrained Coanda jet. A $k - \epsilon$ model is used and the empirical constants of that scheme are optimized for this type of turbulent flow.

An examination of Coanda effect jets over a cylinder and an adjacent surface is a unique study as past Coanda jet examinations involved the flow over unconstrained surfaces as found in V/STOL aerodynamics. Coanda effect jets have been used and studied as lift enhancement devices where they are blown over the trailing edge of wings to delay separation of the flow over the wing and increase the wing circulation and lift. The device proposed here is a distinct departure from those external concepts. This work makes a significant contribution to the field of fluid flow research and applications by examining a device that is being promoted in industry but lacks technical or analytical support. This project report details the effects and characteristics of Coanda jets over a cylinder with an interacting adjacent plane surface.

Background and Review

Coanda Phenomenon

A jet issuing close to a surface shows a strong tendency to attach and remain attached to that surface whether it is concave, plane or convex. The Coanda effect refers to those specific cases where the flow travels over top of a convex surface, one that recedes away from the streamline. Plane wall jets and those into a concave surface exhibit very different characteristics and control mechanisms. If the wall is concave the stream's inertial (centrifugal) forces force a contraction of the boundary layer.

The Coanda phenomenon is characterized by a balance of inertial and normal direction pressure gradient forces. For a wall jet the boundary layer (BL) is energized and this generates a lower pressure near the surface than in the free stream. Another description is that the mainstream tries to entrain fluid from both sides of the jet, and thus pumps fluid from the boundary layer region creating the low pressure. This low pressure pulls the stream toward the surface. This normal pressure gradient balances the jet's inertial resistance to turning. Discovery of the phenomenon is commonly attributed to Henri-Marie Coanda who invented and tried to market several applications of the concept before turning his attention to other endeavors.¹ Henri-Marie was born in Bucharest, Rumania in 1885 and later worked in Germany and France. Debate also mentions that Osborne Reynolds played with the Coanda effect in some of his extensive adventures in fluid flow; if true this would have occurred before Coanda's time by a few years.

As with other wall jets, a Coanda jet continuously entrains fluid, causing the jet width to increase and the velocity to decrease. Real fluid flows along a convex surface will eventually separate due to viscosity. As the jet travels, viscosity reduces the jet's thrust and

lets the pressure rise. Eventually an adverse pressure gradient occurs at the surface and the flow separates.

Coanda Jets To Enhance Aircraft Lift and Other Applications

Many examples of applied Coanda jet flows can be drawn from Kohlman's review of V/STOL aircraft design concepts.² The objective of these aircraft is to increase the vertical lift to weight ratios of the vehicles so lower speeds are possible and aircraft can be landed on shorter fields, thus increasing their capabilities for certain situations. One method of increasing lift is to use circulation control wings and the first example below illustrates this where a jet issues on the top surface and adheres to the circular tail portion preventing boundary layer (BL) separation, increasing the effective length and thereby increasing lift.^{3, 4, 5, 6, 7}

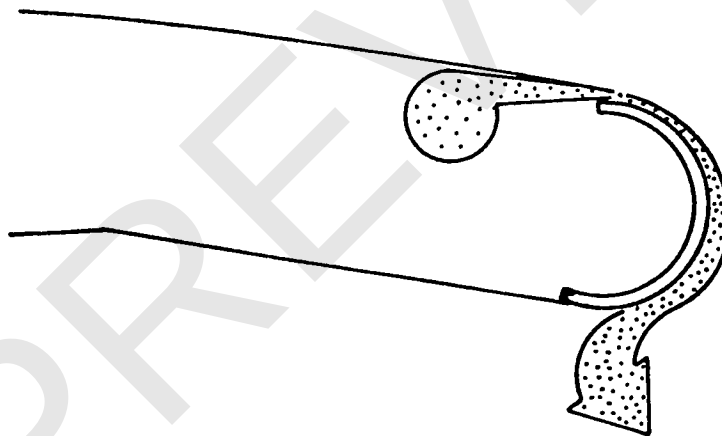


Fig. 2 Trailing edge of a circulation control wing.²

This type of blown flap was tested on the A-6 STOL Demonstrator designed and built by Grumman Corporation.⁸ The predicted performance was demonstrated with a 30% reduction in takeoff and approach speeds, and a 50% decrease in required ground space. In addition to the blown flaps and thrust vectoring used, this airplane employed an enlarged

horizontal rear stabilizer and enlarged fin and rudder to help maintain control during low speed operation.

Another example of a high lift system for aircraft is the augmentor wing section shown below. In this case an ejector jet is used to entrain air into the channel between wing flaps and increase the jet flap momentum coefficient. Ejectors were studied by Maroti, Hill, Armstrong and Haines in a 1976 initiative investigating lift enhancement techniques.⁹ While their experimental and analytical results are not directly applicable to the study here, they do present an alternative design scheme of placing the jet away from the curved Coanda surface and entraining an interior, secondary flow in addition to entraining the tertiary freestream.

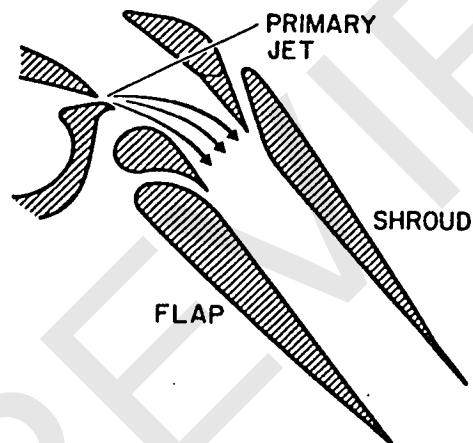


Fig. 3 Typical augmentor wing section.²

The "Jetwing" design described by Sinha, Kimberlin and Wu is a more radical approach than most other jet-enhanced circulation ideas in that it redirects *all* of the jet exhaust stream to blowing slots located on top of and near the front of the wings.¹⁰ Most other developers propose only partially utilizing the exhaust gases or provide a separate pumping system altogether. The diagram below illustrates the wing cross section and includes a second small upper wing. The obvious practical problem of dealing with high temperature gases may make this a difficult design to implement.

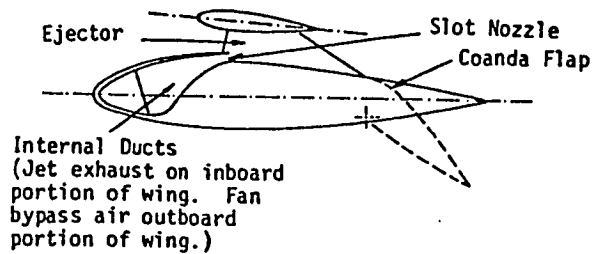


Fig. 4 Two-dimensional view of "Jetwing" concept.¹⁰

The previous examples have outlined concepts used for aircraft to reduce take-off lengths but are not capable of hover or vertical take-off. Kohlman presents a Coanda jet-configured winged craft that may be able to take off vertically and it is illustrated below. For this aircraft, substantially larger ejector jets are used and, similar to the concepts above, entrain flow to increase the momentum coefficient and augment the jets' performance. The hover configuration is shown below. For forward motion the various flaps forming the vertical jet would be rotated to close off the channel and help form a wing for standard flight.

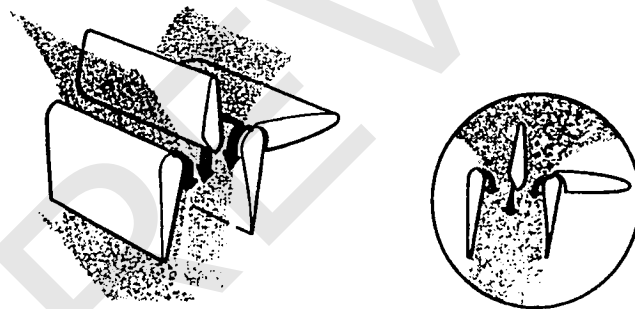


Fig. 5 Ejector and diffuser configuration on the thrust augmented wing.²

Supersonic jet flows were studied by Bevilaqua and Lee in the interest of reducing the impact of shock waves as they tend to cause premature separation of the jet flow, eliminating the advantage of Coanda flow over the trailing wing edge.¹¹ Their results indicate that a convergent/divergent nozzle is recommended to expand the jet stream and avoid the severe shocks that result with an underexpanded jet. Measurements of surface pressure for a

Coanda flow over a cylinder were provided and can be used in this study to help validate modeling schemes.

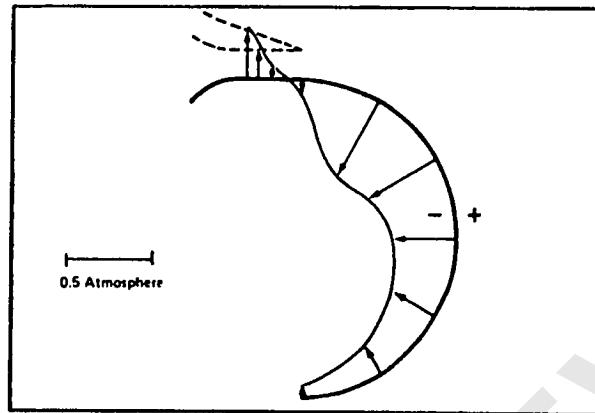


Fig. 6 Coanda surface pressure outside a "Symmetric" nozzle.¹¹

Aircraft designers and operators tend to be a conservative lot due to the emphasis placed upon safety and reliability, so the innovative concepts described above have reached only the experimental and prototype stage, except in isolated high performance or fighter applications.

Blowing jet technology over the trailing edge of wings has been proposed for large transport class aircraft for military uses. In the early 1970's the U.S. was evaluating replacements for the C-130 with Douglas Aircraft and Boeing proposing planes incorporating blowing jets, be it with different approaches. One of the driving factors of the transport plane design was short field capability achieved by wings with increased circulation. The McDonnell Douglas YC-15 design captured the exhaust gases from underwing engines and funnelled them to the top surface of the trailing flaps to form wall jets over the flaps.¹² Increased lift is gained from both increased wing circulation and the deflection of the jet thrust; a 90% turning efficiency was claimed. The Boeing model placed the engine on the upper surface of the wing where the exhaust jet remains attached over the

entire span and then over the trailing flaps, creating thrust deflection and "supercirculation."¹³

Helicopters have been proposed that also use blowing slot techniques on the trailing edges of rotors to similarly increase lift. Williams of the Naval Ship R & D Center describes a craft designed for high speed cruise and VTOL that uses a rotor with a blown trailing edge that is radically different from conventional helicopter rotors in its size and profile.¹⁴ The Naval initiative drew upon experiments performed on rotor shaped wings with blowing slots at the University of Maryland as reported by Englar.¹⁵ This work is different from other experiments performed during this time period in its use of novel measuring instruments and small Coanda surface cylinders (1 - 2 inch radius).

Another application of Coanda jet technology is for Coanda Flare combustors as described by Gilchrist and Gregory-Smith and shown below.^{16,17} The principle of operation here is that the jet of high pressure burnable gas turns over the Coanda surface, experiences increased entrainment and turbulent mixing and therefore promotes combustion and reaction. The source of gas is in practice at a pressure so that the flow is always choked and this brings up the problem of shock waves and separation caused by the same. The analysis and experimentation presented in these references addressed the flow structure and the shapes of the jet over the surface. It is yet to be determined if this asymmetric burner is advantageous when compared to more conventional designs. The Coanda surface will impose some heat transfer effect and the lack of oxidizer on the inner surface of the jet will corrupt combustion.

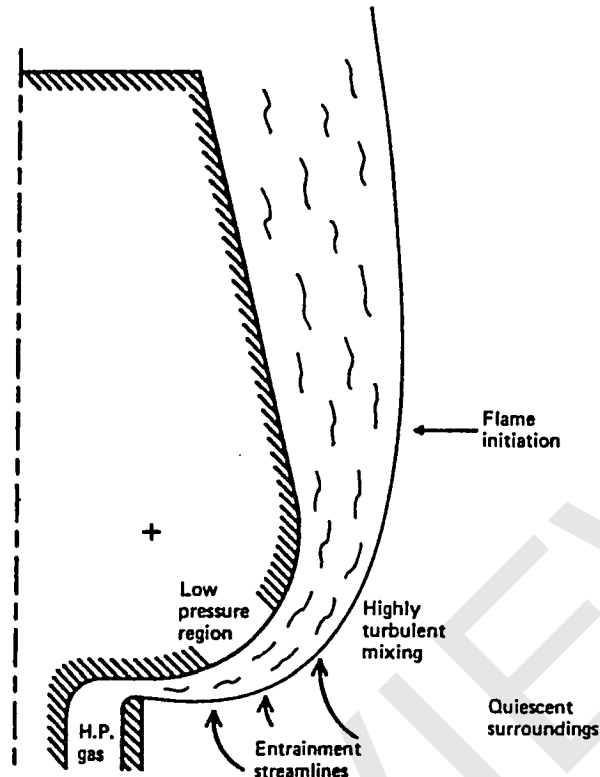


Fig. 7 The Coanda Flare concept.¹⁷

Unconstrained Coanda Jets Around a Cylinder

Newman presented a cursory introduction to the Coanda jet flow around a cylinder in a stagnant environment.¹⁸ He compared some experimental results with analytical techniques assuming known profile shapes and estimated jet boundary growth, and developed equations to predict jet separation points and other characteristics. The geometry and nomenclature for his work are shown in Fig. 8 and will be maintained throughout this document.

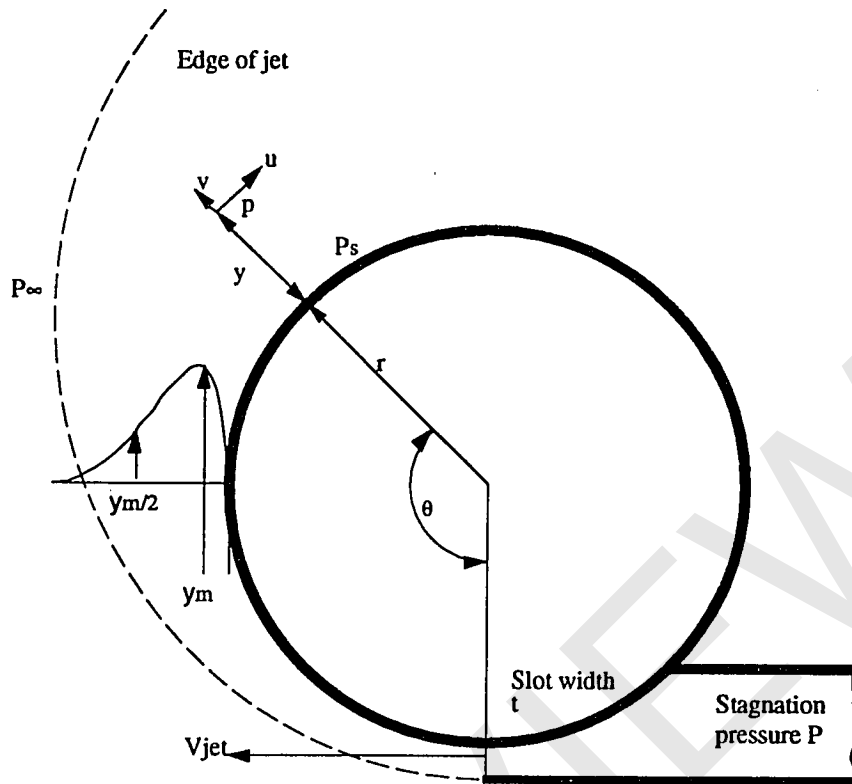


Fig. 8 Flow of a two-dimensional jet around a circular cylinder.

Numerous experimental studies were compiled to develop correlations to describe and predict the jet profile and characteristics. The profile shape is predicted by Newman with the relation below:

$$\frac{y_{m/2}}{r \Theta} = 0.11 \left(1 + 1.5 \frac{y_{m/2}}{r} \right) \quad (\text{eq. 1})$$

The surface pressure distribution is estimated as

$$\frac{(P_{\infty} - P_{\text{surf}}) r}{(P - P_{\infty}) b} = \frac{8 \ln \left(1 + \frac{4 y_{m/2}}{3 r} \right)}{\left[\left(\frac{4 y_{m/2}}{3 r} + 1 \right)^2 - 1 + 2 \ln \left(1 + \frac{4 y_{m/2}}{3 r} \right) \right]}, \quad (\text{eq. 2})$$

and the position of separation is believed to be the following for a turbulent constant Reynolds number: