Surface Pressures on a Flat Plate with Dual Jet Configurations

Joseph A Schetz*and Antoni K Jakubowski†
Virginia Polytechnic Institute and State University
Blacksburg, Virginia
and
Kiyoshi Aoyagi‡
NASA Ames Research Center, Moffet Field, California

A jet in a crossflow is of interest in numerous practical situations including jet powered VTOL aircraft Two aspects of the problem have received little prior study, first, the effect of jet angle to crossflow, and second, the performance of dual-jet configurations both in line and side by side The test plan for this work was designed to address these two aspects The experiments were conducted in the Ames 7×10 ft Wind Tunnel at velocities ranging from 14 5 35 8 m/s (47.6 117 4 ft/s) Detailed pressure distributions are presented for single and dual jets having velocity ratios ranging from 3 to 8, spacings ranging from 2 to 6 diameters, and injection angles of 90, 75, and 105 deg Shown here are the effects of the various parameters, as well as the contrasting effects of axisymmetric and flat plate geometries on the nature, size, shape, and strength of the interaction regions on the body surfaces

Nomenclature

C_p = pressure coefficient
ΔC_p = pressure coefficient difference, $(C_{p_{\text{jet on}}} - C_{p_{\text{jet off}}})$
D = diameter
$\dot{m}$ = mass flow rate
P = pressure
q = dynamic pressure
R = nominal velocity ratio
S = center to center jet spacing
T = temperature
V = velocity
x = streamwise coordinate measured from center of the front nozzle
X = x/D
y = transverse coordinate measured from nozzle center; plus (+) is to the right, looking downstream
y = y/D
δ = boundary layer displacement thickness
θ = injection angle measured upwards from the horizontal, looking downstream
ρ = density

Subscripts

b = main body
j = jet conditions
∞ = freestream conditions
$\bar{()}$ = average quantity over jet exit

Introduction

THE flowfield of a jet in a crossflow is of interest in a number of practical situations, including smokestacks, sewage outfalls chemical mixing operations and jet powered VTOL aircraft The available information on this general flow is discussed in Ref 1 Since, for the VTOL application, the pressure field induced on adjacent surfaces is of particular importance, there have been a number of detailed ex perimental studies of that part of the flowfield covering many of the important variables and parameters [2 12] Reviews of the early work can be found in Refs 13 and 14 and a tabulation of the available information is contained in Ref 15 The jet generally induces negative (with respect to the freestream) pressures on the nearby surfaces, and this results in a net loss of lift on the body viewed as a whole The longitudinal variation of the surface pressures is also important, since that determines the resulting pitching moment

There are two aspects of the general problem that have received little careful study The first is the effect of jet angle with respect to crossflow This effect is important because the transition to wingborne operation is usually accompanied by a change in the angle of the jet thrust vector There are few prior investigations in the literature [8 11 16] The second item is the performance of dual jet configurations, either in line or side by side The mutual interference as a function of center to center spacing is the issue here Again, few references exist [3 8 17] Also, the interplay of these two items over a range of the key parameter for all such flows ($R \equiv V_{\text{jet}}/V_{\text{stream}}$) is clearly of importance to the designer

There have also been analyses both conventional and semiempirical, of the jet in a crossflow problem [15 19 28] However, at the moment none can treat in a fundamental way a combination of the two items selected here for study The experimental studies reported here should aid in the generalization of the existing analyses

The test plan for the present work was designed to provide new information on the influence of the two effects chosen for investigation: 1) injection angle, and 2) in line and side by side jets

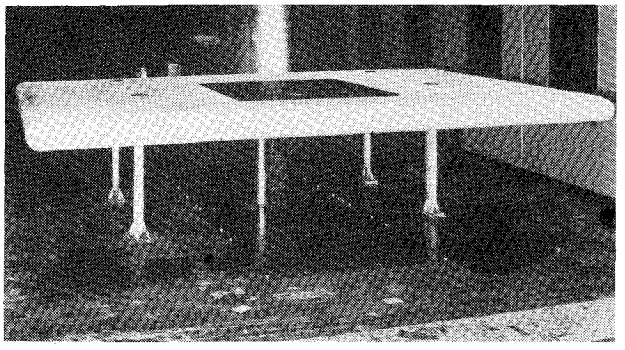
Apparatus

Facility

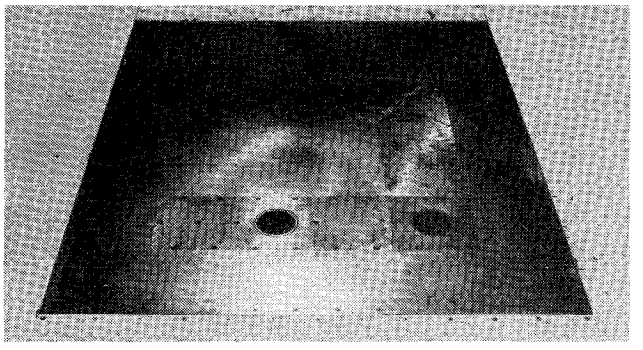
The experiments were conducted in the 7×10 ft (2 13×3 05m) Subsonic Wind Tunnel at the NASA Ames Research Center at velocities ranging from 14 5 to 35 8 m/s (47 6 to 117 4 ft/s) depending upon the jet/freestream velocity ratio desired This facility is described in Ref 29

Received July 29 1983; revision received Dec 29 1983;

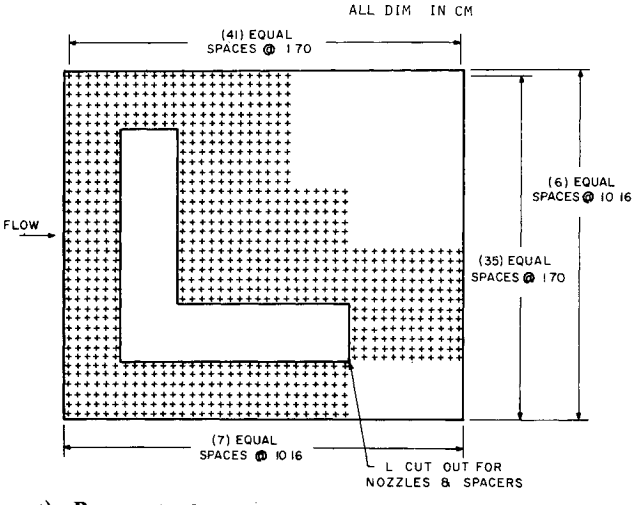
*Professor and Head, Aerospace and Ocean Engineering Department Associate Fellow AIAA
†Associate Professor Aerospace and Ocean Engineering Department Member AIAA
‡Aerospace Engineer Member AIAA



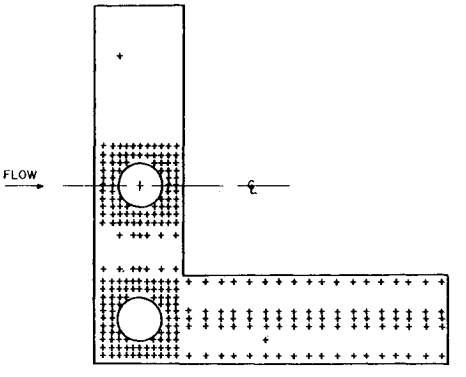
a) Photograph of the model in the wind tunnel



b) Close up of the nozzle section



c) Pressure top layout in the instrumented section of the model



d) Pressure top layout in the nozzle and space section

Fig 1 Flat plate model

Test Model

The model is shown in Fig 1 It has a streamlined leading edge and the bottom is covered with a fairing There is a large L shaped cutout section created to accommodate the injector and spacer sections in various combinations These com binations produce the required different center to center jet spacings in either the aligned or side by side arrangements Each nozzle is located in a 10 16 cm (4 0 in) square section There are a number of spacer sections either 5 08 cm (2 0 in) or 10 16 cm (4 0 in) long occupying the areas ahead of between, and behind the nozzle sections in the arrangements for the various jet spacings The jets had a 4 92 cm (1 94 in) exit diameter The front (or looking downstream the right) injector section always remained in the same place The pressure tap layouts for the injector and spacer sections are shown using the 90 deg injector as an example Part of the fixed portion of the plate is also instrumented with pressure taps

A relatively uniform jet exit velocity profile for all injection angles was desired since nonuniformities in jet exit profiles have been shown to influence the surface pressure field [12] The injector design finally chosen is shown for the 90 deg injector in Fig 2 The air is supplied via four tubes that entered the bottom The air leaves the vents through four holes around the vent periphery This configuration was selected in an attempt to distribute the entering flow over the cross section of the short (in the flow direction) plenum Located above the vent exits is a perforated plate with the hole pattern shown which serves as the next step in the flow distribution process This hole pattern was refined by trial and error and different patterns were required for the other injection angles Above the perforated plate is a smooth contraction which runs down to the jet diameter This is followed by a flow straightener

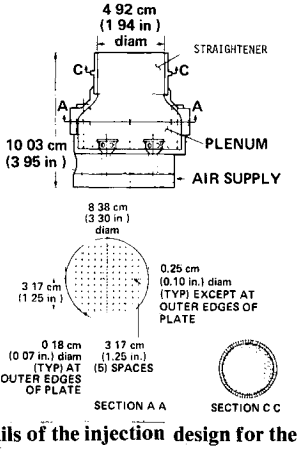


Fig 2 Details of the injection design for the 90 deg case

insert which consists of a thin wall tube holding a honeycomb with screening top and bottom The purpose of the large length/diameter honeycomb is to force all of the flow in the same direction The purpose of the screens is to lessen any remaining nonuniformities by accelerated turbulent mixing

The primary instrumentation for all the tests was a group of 48 port Scanivalves The integrity of each Scanivalve lead line from the pressure taps was carefully checked on a one by one basis by applying a known pressure to the tap at the model surface and reading the output from the Scanivalve The Scanivalves were operated and the data was obtained in teractively by the data acquisition system for the 40×80 and 7×10 ft wind tunnels at Ames Research Center All the data was recorded on tape for subsequent data reduction

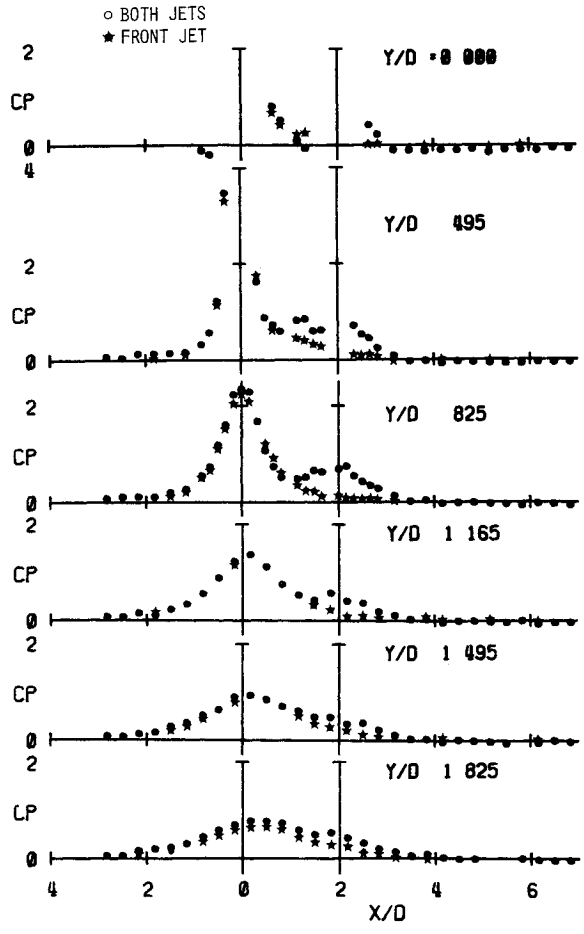


Fig 3 Surface pressure distribution (ΔC_p), flat plate model, 90 deg; $R=6$, $S/D=2$

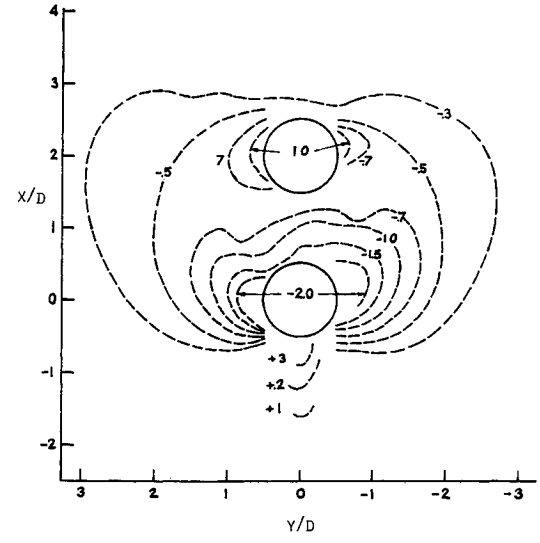


Fig 4 Isobar map of ΔC_p, flat plate with both jets 90 deg; $R=4$, $S/D=2$

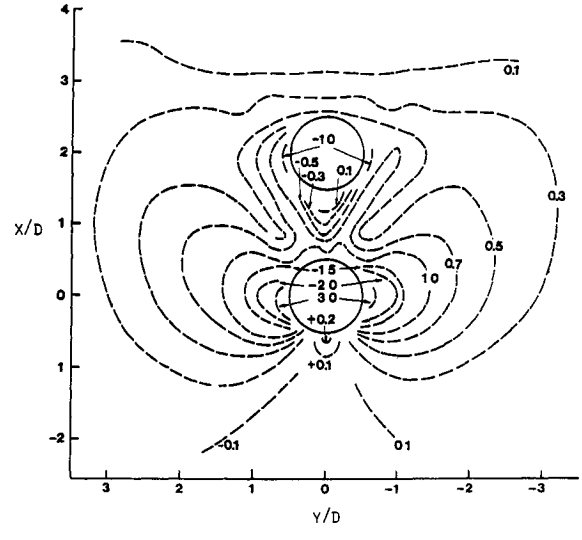


Fig 5 Isobar map of ΔC_p, flat plate with both jets 90 deg; $R=6$ $S/D=2$

All the other necessary measurements were also run through the data acquisition system These included pressure measurements for tunnel speed, orifice readings for injector mass flow, and temperature readings for the tunnel and in jector air flows The barometer and room temperature were read by eye and the information was entered manually into the data acquisition system

Test Plan and Procedures

The desired range of jet to freestream velocity ratios can be obtained by a variety of paths, including holding the freestream velocity constant and varying the jet velocity or vice versa Testing at a constant freestream velocity is at tractive because that would keep the body Reynolds number and hence, the boundary layer thickness constant However the difficulties and effort required to achieve reasonably uniform jet exit velocity profiles over a 3:1 ($3 \le R \le 8$) range in jet average velocity was judged to be so severe as to justify the choice of holding the jet velocity fixed and varying the freestream As a check on the influence of the body Reynolds number variation thus introduced one case at the same R but with different freestream velocity, was included for most configurations tested Only small effects were found

There were three other constraints that influenced the test plan First, it was considered important to keep the minimum body Reynolds number, based on the surface distance to the first nozzle above roughly 5×10^5 in order to have a turbulent boundary layer This meant a freestream velocity above a value of about 13 m/s Second to avoid the added complexity of strong compressibility effects, it was decided to keep the maximum jet velocities roughly below 120 m/s ($M_j < 0$ 35)

Lastly the pressure drop through the most severely inclined injectors was large enough to limit the mass flow (and thus the jet velocity) that could be obtained for those con figurations

Taking all of the items above into account, a test plan was adopted which had a nominal jet volume flow rate of 0 214 m^3/s corresponding to $\bar{V}_j = 112$ 5 m/s and freestream velocities corresponding to $1\ 28 \le q \le 8\ 03$ cm H_2O ($14\ 5 \le V_\infty \le 36\ 2$ m/s)

Each test series was run as follows First, the data acquisition system was run to obtain ' null" readings and calibration settings The air supply pressure settings corresponding to the set of injectors in use were then brought up and adjusted Next the tunnel was turned on to the lowest speed in the series The data acquisition system was run The tunnel speed was adjusted to the next setting and the process was repeated over the range desired The last point in each series was a single value of R achieved at a combination of tunnel and jet speed different from the point at the same R in the main series The tunnel and air supply were turned off and "null" readings were again taken

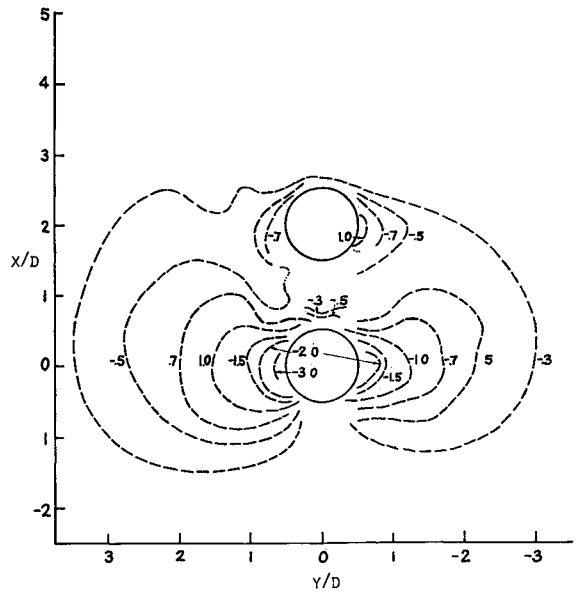


Fig 6 Isobar map of ΔC_p flat plate with both jets, 90 deg; $R=8$, $S/D=2$

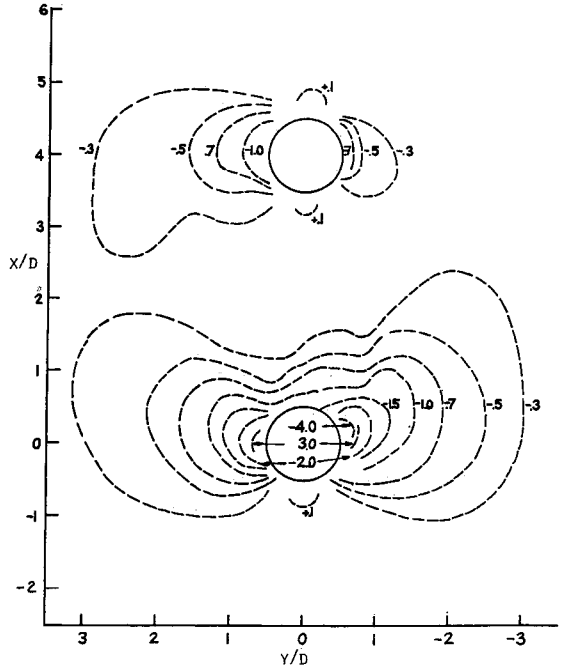


Fig 8 Isobar map of ΔC_p flat plate with both jets, 75 deg; $R=6$, $S/D=4$

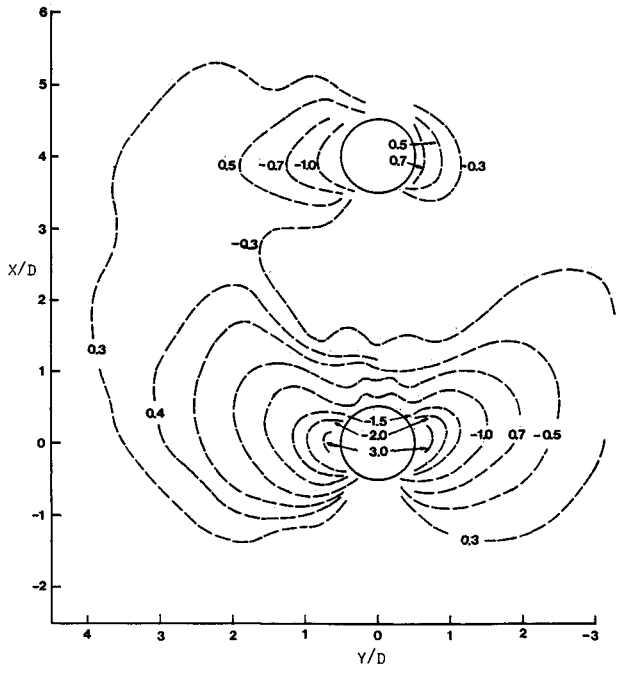


Fig 7 Isobar map of ΔC_p flat plate with both jets, 90 deg; $R=6$ $S/D=4$

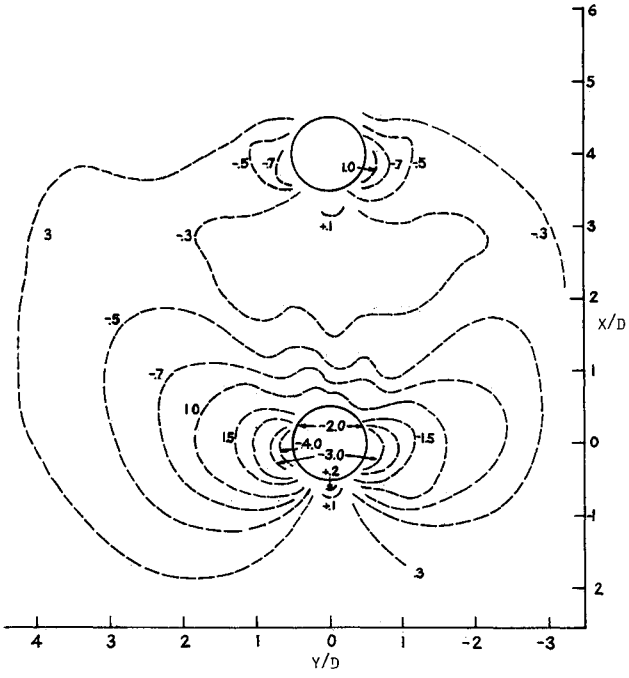


Fig 9 Isobar map of ΔC_p flat plate with both jets 105 deg; $R=6$ $S/D=4$

Results

The data were reduced and the results are presented here as

$$\Delta C_p = (C_{p_{\text{jet on}}} - C_{p_{\text{jet off}}})$$

which is a function of spatial location on the body surface for each configuration In this way, the first order effects of any asymmetries or surface irregularities on the models should be normalized out Before being accepted, each set of data was measured against certain criteria For example was the mass flow (and thus $\bar{V}_j$) set close enough to the desired nominal conditions? For the two jet tests were the mass flows set close enough to each other? (For these items a tolerance of roughly ± 5% was adopted) When combined with the actual tunnel speed for a given data point, was the desired value of R again achieved roughly ± 5%? These questions were important since we wished to make such case to case comparisons as the effect of jet spacing holding R nominally fixed, etc

Longitudinal pressure distributions at selected lateral distances are plotted in Fig 3 for the 90 deg injectors at $R=6$ with a spacing of two diameters and the jets aligned one behind the other The results for both jets are shown as cir cles; those for the front jet are stars

Looking at the singlc jet results first, the expected pattern of negative ΔC_p's is evident The dual jet results show that the influence of the rear jet is less than that of the front jet at this

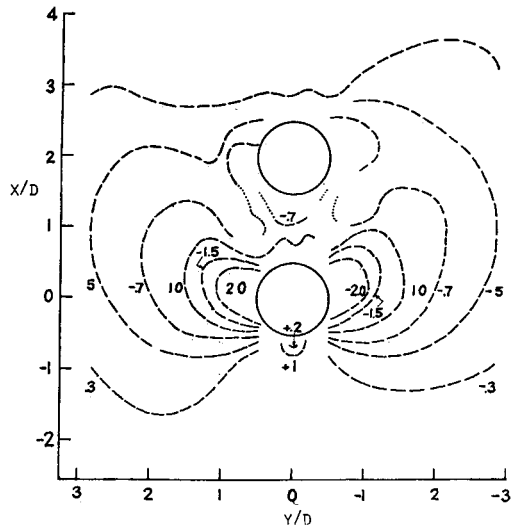


Fig 10 Isobar map of ΔC_p, flat plate with both jets, 75 deg; $R=6$ $S/D=2$

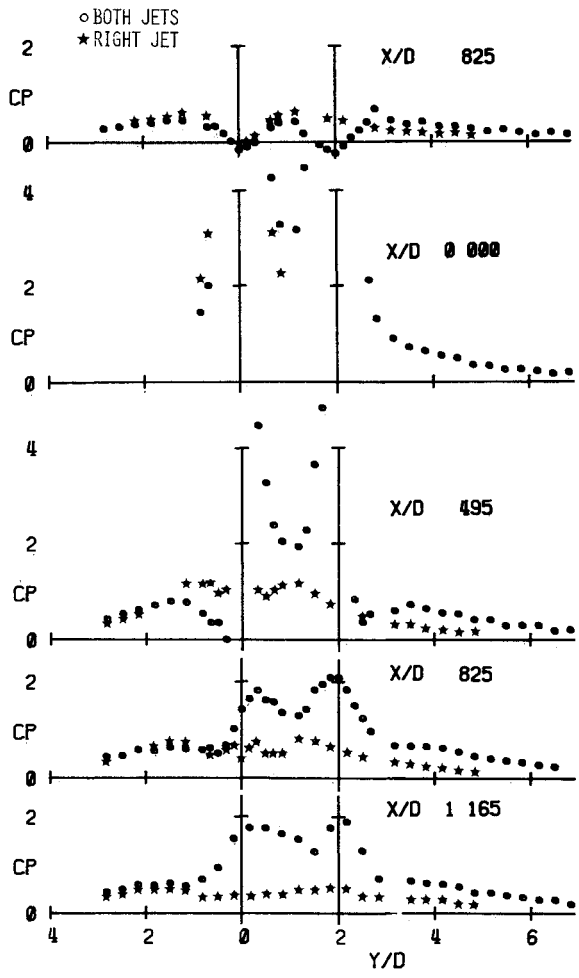


Fig 11 Transverse surface pressure distribution (ΔC_p) flat plate model, 90 deg; $R=6$ $S/D=2$ side by side

close spacing On the other hand the presence of the rear jet seems to strengthen the influence of the front jet slightly The data in Fig 3 can be roughly compared to the data in Fig 6 of Ref. 30 for 90 deg injection with $S/D=2$ 0 from a body of revolution at $R=7$ 7 First one finds that there are no positive ΔC_p values behind the second jet on the first plate Second the peak values on the body of revolution are

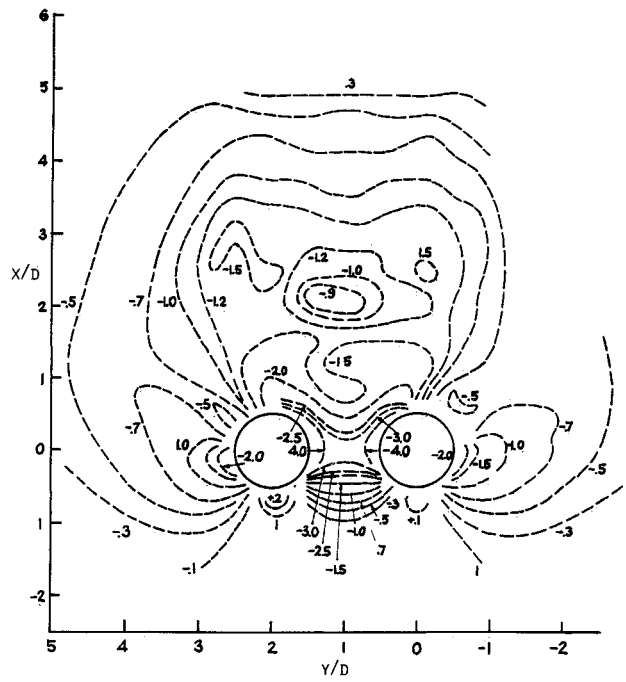


Fig 12 Isobar map of ΔC_p, flat plate with both jets, 90 deg; $R=6$, $S/D=2$, side by side

somewhat higher very near the nozzles Third, by comparing values at $y/D=0$ 8, it can be seen that the peak values decay faster with lateral distance on the body of revolution

The effects of the important parameter R can be seen in the isobar plots in Figs 4, 5, and 6 for $R=4$, 6, and 8 As R in creases the area of the surface influenced by the jets in creases This increase is mostly in terms of the areas with small to moderate negative values of ΔC_p The area with $\Delta C_p \leq -1$ 0 does not change significantly with R Since the area of influence increases with R, the total normal force also increases with R, but the increase is slow Thus, the value of the total normal force normalized with the thrust of the jets actually decreases with increasing R The effective center of normal force moves forward with increasing R Estimates indicate that this center coincides with the center of the front jet at about $R=10$ Lastly, the shape of the interaction region changes with increasing R At low R the isobars show asymmetrical lobes displaced in the downstream direction At higher R there is less downstream distortion Compare Fig 4 at $R=4$ to Fig 6 at $R=8$

The present results in Fig 6 can be roughly compared with those of Wooler et al in Ref 31 at $R=8$, but with S/D=2 5 as opposed to our S/D=2 0 The comparison is made dif ficult since the tests in Ref 31 did not have as detailed a coverage of the area near the jets Nonetheless comparison of the $\Delta C_p=-0$ 5 isobars, for example, shows rather good agreement in terms of overall shape and axial and lateral extent.

The effects of increasing the dimensionless spacing S/D from 2 to 4 with 90 deg and $R=6$ are shown in Fig 7 Here as for the body of revolution data in Ref 30, the rear jet is still sheltered by the front jet, and the influence of the front jet on the flow is reduced by the presence of the rear jet Looking at the isobar patterns in Fig 7 and comparing them with those in Fig 5 for the same case with $S/D=2$ it can be observed that the overlap of the interaction regions of the two jets is now for small ΔC_p values only By comparing isobar plots with the front jet only (not presented here due to space limitations) with those for both jets operating, it is shown that the interaction of the two jets increases the surface area influenced by the front jet It was also found that the merging of the interaction regions was influenced by the velocity ratio R The merging is most pronounced at low R values Also the

sheltering of the rear jet reduces the downstream distortion of its flow interaction area

The influence of injection angle at $R=6$ is shown in the next two figures. Fig 8 has results for a 75 deg angle (15 deg downstream), and Fig 9 has results for injection at 105 deg (15 deg upstream), all at $S/D=4$. The isobar plots in Figs 8 and 9 and the plot for 90 deg in Fig 7 show some interesting effects The change from 75 to 90 deg produces only slight changes in the total interaction area influenced by the jets and, thus, in the normal force However, the change from 90 to 105 deg leads to an increase in the total interaction area and hence the normal force Further as the angle goes from 75 to 90 to 105 deg, the effective center of the interaction region moves forward The data indicate that the region ahead of the front jet is influenced somewhat more strongly by upstream angled injection In addition the sheltering of the rear jet by the front jet is stronger for 105 deg than for the 90 or 75 deg injection

The result of reduced spacing to $S/D=2$ at 75 deg and $R=6$ can be noted by comparing Fig 10 with Fig 8 for $S/D=4$ The effects are generally the same as for the 90 deg injection

The next series of figures presents the results obtained with two jets in a side by side arrangement Due to test time limitations fewer parameters were varied in this con figuration All the data obtained are for the 90 deg injectors only

Transverse pressure distributions at five axial stations including one ahead of the jets, are shown in Fig 11 for $R=6$ and $S/D=2$ Data for only the right jet operating are shown as solid circles The presence of the left jet has a slight effect on the right jet at the station ahead of the jets ($x/D=-825$), but the interference effect is quite large at $x/D=0$ and the downstream stations High (negative) ΔC_p values are ob tained between and just downstream of the jets Also the right/left symmetry of the flow was found to be good for single and dual jet runs An isobar map for the same case is given in Fig 12

Figures 13 and 14 show isobar maps for $S/D=2$ with $R=4$ and 8 By comparing these with the previous figure, the ef fects of R can be seen As R is increased, there is a pronounced increase in the size of the interaction region around the jets The interaction normal force also increases, both as a result of the increase in area affected and increases (negative) in the ΔC_p values near the orifices The effective center of the interaction force shifts upstream as R is in creased Collectively, these results indicate a strong increase in

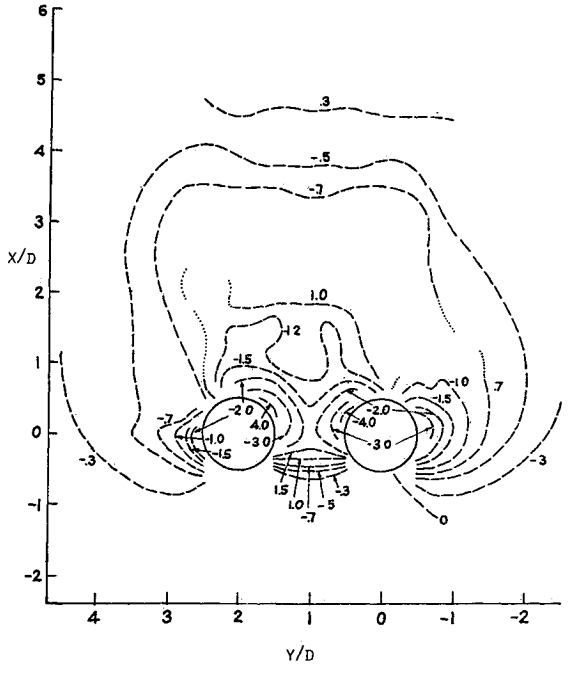


Fig 13 Isobar map of ΔC_p, flat plate with both jets, 90 deg; $R=4$, $S/D=2$, side by side

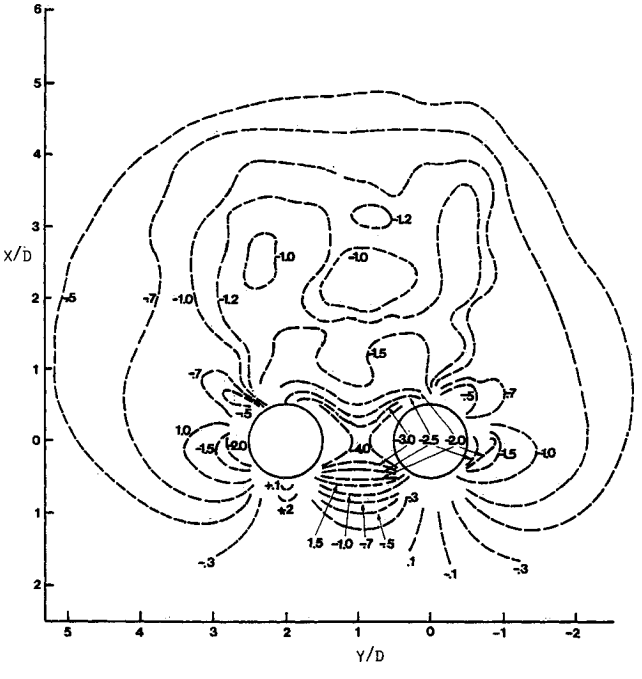


Fig 14 Isobar map of ΔC_p flat plate with both jets, 90 deg; $R=8$, $S/D=2$, side by side

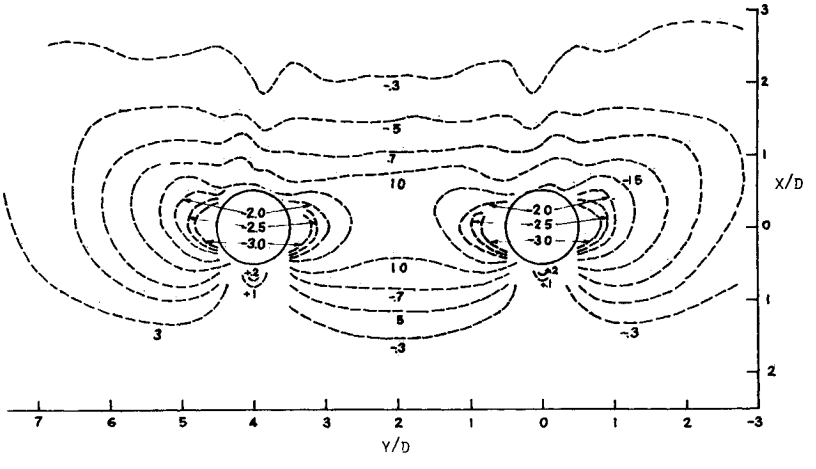


Fig 15 Isobar map of ΔC_p flate plate with both jets, 90 deg; $R=6$ $S/D=4$ side by side

the interaction between the two jets as R is increased at this close spacing The large (negative) ΔC_p values in the region immediately behind the jets along the line of symmetry between them at high R values are noteworthy This is probably a result of the interaction between the pairs of counter rotating vortices formed in each jet

The influence of increasing S/D to 4 at $R=6$ can be seen by comparing the results in Fig 15 to those given earlier for $S/D=2$ at the same R in Fig 12 The interaction of the jets is diminished significantly Looking at the isobar maps one can see that there is much less overlap of the interaction regions of the two jets at $S/D=4$ The overlap or merging of the in teraction regions is R dependent; it is strongest at the higher R values The interaction region of each jet on the "free" side (the side away from the other jet) is still always larger than for the single jet even at $S/D=4$ This is probably due to a blocking effect The main flow approaching the side by side jets is partially "blocked" in the center region and "spilled over" around the sides resulting in more fluid flow and higher velocities (and lower pressures) on the free side of the jets

Conclusions

In Line Jets

The mutual interaction of the jets results in sheltering of the rear jet by the front and in some cases "swelling" of the front jet because of the presence of the rear jet Due to the latter effect the surface area influenced by the front jet tends to be greater than for the case of a single jet

Increasing R increases the surface area influenced by the jets and the effective center of the normal force moves forward with increasing R from a location between the jets to one near the center of the front jet at about $R=10$

Obviously, increasing S/D diminishes the interaction ef fects of the jets

Varying the injection angle from 75 to 90 to 105 deg moves the effective center of the interaction region forward The upstream angled injection appears to strongly affect the overall pressure distributions

Side By Side Jets

For the side by side jets, gross interaction features are characterized by two interrelated effects: 1) significantly enhanced flow velocity (and thus reduced surface pressures) between the jets due to the "channeling" of the flow between the jets, and 2) increased (when compared with the single jet) blocking of the crossflow and spill over to the sides which results in increased flow velocities (lower pressures) on the free sides of the jets.

Increasing R magnifies the interaction effects and the resulting forces The downstream region, in particular, is strongly affected because of the strong interaction between the near wake portions of the jets

Increasing S/D reduces the interaction effects

References

[1]Schetz, J A *Injection and Mixing in Turbulent Flow* AIAA New York 1980

[2]Vogler R D ' Surface Pressures Distributions Induced on a Flat Plate by a Cold Air Jet Issuing Perpendicularly from the Plate and Normal to a Low Speed Free Stream Flow NASA TN D 1629 1963

[3]Vogler R D Interference Effects of Single and Multiple Round or Slotted Jets on a VTOL Model in Transition ' NASA TN D 2380 1964

[4]Bradbury L J S. and Wood M N 'The Static Pressure Distributions Around A Circular Jet Exhausting Normally From a Plane Wall Into an Airstream, C P No 822 British A R C , 1965

[5]Margason R J , Jet Induced Effects in Transition Flight. Conference on V/STOL and STOL Aircraft NASA SP 116 1966 pp 177 189

[6]Gentry Carl L and Margason, Richard J Jet Induced Lift Losses on VTOL Configurations Hovering In and Out of Ground Effect NASA TN D 3166 Feb. 1966

[7]Soullier A Testing at SI MAS for Basic Investigation on Jet Interactions Distributions of Pressure Around the Jet Orifice NASA TTF 14066, April 1968

[8]Fricke, L B , Wooler P T and Ziegler H A Wind Tunnel Investigation of Jets Exhausting Into a Crossflow AFFDL TR 70 154, Vols I IV U S Air Force Dec 1970

[9]Margason R J , Review of Propulsion Induced Effects on Aerodynamics of Jet/STOL Aircraft ' NASA TN D 5617, Feb 1970

[10]Fearn, R L and Weston R P , Induced Pressure Distribution of a Jet in a Crossflow ' NASA TN D 7916 June 1975

[11]Taylor P An Investigation of an Inclined Jet in a Crosswind *Aeronautical Quarterly* Vol XXVIII Part I Feb 1977

[12]Kuhlman J M Ousterhout D S and Warcup R W Experimental Investigation of Effects of Jet Decay Rate on Jet Induced Pressures on a Flat Plate: Tabulated Data NASA CR 158990 Nov 1978

[13]Lee C C ' A Review of Research on the Interaction of a Jet With an External Stream [Contract No DA 01 021 AMC 11528(z)] Research Lab , Brown Engineering Co Inc Tech Note R 184 March 1966 (Available from DDC as AD 630 294)

[14]Garner, J E ' A Review of Jet Efflux Studies Application to V/STOL Aircraft, U S Air Force AEDC-TR 67 163 Sept 1967 (Available from DDC as AD 658 432)

[15]Perkins S C Jr and Mendenhall M R A Study of Real Jet Effects on the Surface Pressure Distribution Induced by a Jet in a Crossflow NASA CR 166150 March 1981

[16]Margason R J The Path of a Jet Directed at Large Angles to a Subsonic Free Stream, ' NASA TN D 4919 Nov 1968

[17]Ziegler H and Wooler P T Analysis of Stratified and Closely Spaced Jets Exhausting into a Crossflow NASA CR 132297 Nov 1973

[18]Ousterbout D S An Experimental Investigation of a Cold Jet Emitting from a Body of Revolution into a Subsonic Free Stream NASA CR 2089 July 1972

[19]Abramovich G N *The Theory of Turbulent Jets* M I T Press Co., 1963, pp 541-552

[20]Wu J C and Wright M A A Blockage Sink Representation of Jet Interference Effects for Noncircular Jet Orifices Analysis of a Jet in a Subsonic Crosswind NASA SP 218 1969 pp 85 99

[21]Street, T A and Spring, J Experimental Reaction Jet Effects at Subsonic Speeds Analysis of a Jet in a Subsonic Crosswind NASA SP 218 1969 pp 63 83

[22]Dietz, W E Jr , A Method for Calculating the Induced Pressure Distribution Associated with a Jet in a Crossflow ' M S Thesis Florida University 1975 (also available as NASA CR 146434 1975)

[23]Yen, K T 'The Aerodynamics of a Jet in a Crossflow ' NADC 78291 60 Dec 1978

[24]Perkins, S C Jr and Mendenhall, M R A Correlation Method to Predict the Surface Pressure Distribution on an Infinite Plate or a Body of Revolution from which a Jet is Issuing NASA CR 152345 Jan 1980

[25]Fearn R L., Kalota C and Dietz W E Jr A Jet Aerodynamic Surface Interference Model ' *Proceedings V/STOL Aircraft Aerodynamics*, Vol 1 Naval Post Graduate School Monterey Calif May 1979

[26]Campbell J F and Schetz J A Analysis of the Injection of a Heated Turbulent Jet into a Cross Flow NASA TR R 413 Dec 1973

[27]Baker A J , Manhardt P D and Orzechowski J A A Three-Dimensional Finite Element Algorithm for Prediction of V/STOL Jet Induced Flowfields AGARD Symposium Lisbon Portugal Nov 1981

[28]Isaac K M and Schetz J A Analysis of Multiple Jets in a Cross flow *Journal of Fluids Engineering* Vol 104 1982 pp 489 492.

[29] 7×10 Wind Tunnel Guide Ames Research Center NASA Oct. 1978

[30]Schetz J A Jakubowski A K , and Aoyagi, K Jet Trajectories and Surface Pressures Induced on a Body of Revolution with Various Dual Jet Configurations ' *Journal of Aircraft* Vol 20 Nov 1983 pp 975 982

[31]Wooler P T Wasson H R Kao, H C Ziegler, H , and Schwandemann M F , V/STOL Aircraft Aerodynamic Prediction Methods Investigation ' AFFDL-TR 72 26 Jan 1972