A NUMERICAL SIMULATION OF A BRUSH SEAL SECTION 
AND SOME EXPERIMENTAL RESULTS

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ABSTRACT

The brush seal technology represents quite a promising advance in the effort of construction of more efficient, and possibly smaller size engines. Conclusions of recent workshops determined that while the brush seals works well, there is a need to improve its performance characteristics. The considerable amount of experimental work performed to date has indicated the importance of the local flow phenomena in the global sealing process performance of the brush (Braun et al., 1990a, 1991b, 1992, Hendricks et al., 1991a). The distributed flow and pressure fields are thus of vital importance for the prediction of the possible sudden failure of the brush seal under unexpected local "pressure hikes". It is in this context that the authors developed a numerical, two dimensional time dependent formulation of the Navier-Stokes equations with constant properties, and included the effects of inertia, viscous and pressure terms. The algorithm is applied to a set of non-compliant multirow, multicolumn pin configurations that are similar to the ones found in an idealized brush seal configuration. While the numerical parametric investigation aims to establish the occurrence of major flow patterns and associated pressure maps, the experimental portion of the paper is aimed at gaining further insight into the relevant flow structures, and thus guide the development of the mathematical and numerical model.

NOMENCLATURE

$C_x(u), C_y(v), C_{xv}(v), C_{xy}(u)$ - 1st order conservative upwind approximation for convective terms

$d$ - pin diameter

$E$ - Euler Nr.

$h$ - channel height

$p$ - pressure

$P_e=\rho U_0^2$, $P_h=\rho U_0^2$, $E_u=1$ (Euler Nr.)

$PTDR_L = S_T/d$ - longitudinal pitch to diameter ratio

$PTDR_T = S_L/d$ - transversal pitch to diameter ratio

$Q_x(p), Q_y(p)$ - 2nd order central finite difference approximation for the pressure terms

$Q(u,v)^{1,2}$ - finite difference approximation of the source terms in the Poisson's equation

$Re_d = \frac{U_0 d}{\mu}$ - Reynolds Nr. based on pin diameter

$S_L$ - longitudinal pitch

$S_T$ - transversal pitch

$t$ - time [sec]

$u,v$ - fluid velocities, m/sec (ft/sec)

$T_0=U_0^2/(\rho U_0^2)$ - time scale

$U,O=U_0$, $U_0=U_0$ - dimensionless velocity in X direction

$V_0=V_0$ - free stream velocity, m/sec (ft/sec)

$x,y$ - dimensionless coordinate

Greek letters

$\mu$ - fluid dynamic viscosity, N.s/m² (lb.s/ft²)

$\gamma$ - pseudo-time step used in the pressure equation iterations

$I$ - real time step

INTRODUCTION

Turbomachine seals control leakage, dynamics, tolerance to boundaries, and manage lubricant flow. As all these functions affect engine performance, it is important to understand both their interdependence, and the fundamental aspects. From the many types of contacting or non-contacting seals that are used in turbomachinery applications, this paper will treat the subject of the brush seal. In particular, we shall present a numerical model for flow in a generic array of brush-like pins and the experimental work conducted for guidance and qualitative validation of the numerical effort.

The brush seal is not a new concept. The reduced leakage, and physical compliance of the brush body to external perturbing factors are features that stand out in turbo-
machinery applications where there are expected boundary variations due to mass flow, brush fibers' compliance pressure, temperature, and time dependent eccentric shaft motion. All these characteristics have made the brush configuration an especially interesting and worthy candidate. The geometric configuration of a brush seal is shown in Fig. 1A. Recently, amongst others, Chupp(1991a) and Braun et al.(1990a, 1991a, 1992) have published extensive experimental information concerning the nature of the flow and pressure drops in a brush, and advanced theoretical formulations that explain the physical concept of sealing and the functionality of the brush seal(Braun et al., 1990b).

The initial concept of such a seal has been investigated by General Electric many years ago(1955) under the J-47 engine test program. In the 1980's, Rolls-Royce(RR), has successfully introduced a brush seal on a demonstrator engine(manufactured by Cross Mfg Ltd.(CML)), and tested it for several thousand hours(Fergusson, 1988). More recently EG&G Sealol, Technetics, Detroit-Allison and others have enabled full programs of study of this type of seal. Unfortunately, much of the data generated by industry is restricted, and therefore not a subject of the following brief review.

Following experiments done by CML, Flower(1990) cited leakages that are approximately 5% to 10% of those found in finned labyrinth configurations. It was approximated that one brush is the equivalent to four or five labyrinth cavities having similar size. Experiments by CML have been eventually incorporated in the RR design of the IAE V2500. Allison has also reported successful incorporation of brush seals in some of their engines. According to Holle and Krishnan(1990), the T800 engine was tested with a brush seal located at the turbine discharge, while the T406 Plus engine contained 13 brush seals between the compressor and interstages. Experiments performed at Teledyne CAE, and reported by Hendricks et al.(1991a) have also shown that the leakages are reduced by a factor of four to seven, and the leakage performance follows a hysteresis curve dependent on the shaft speed excursions. Configurations that contain series of brushes, allow higher pressure drops, are more insensitive to shaft speed excursions, and reduce the leakage level. Gorelov et al.(1988) examined the effects of the brush seal's geometric parameters on the leakage flow rate of air, and compared them with data available from labyrinth seals. Blake(1978), investigated the feasibility of using brush seals to seal roller bearing housings.

Applying the Full Flow Field Tracking(FFFT) method, Braun et al.(1990a, 1991a, 1992) studied non-intrusively the fundamental flow patterns and reconstructed graphically the fluid velocities inside a cascade of brushes. The flow field that was visualized by means of a light sheet, and FFFT, revealed regions that are characterized by river jetting, vortical, spatial and temporal, and affect changes in seal leakage and pressure drops. The authors showed that the pressure drop phenomena in the sealing process is fundamental and it can not be simulated by lumped bulk flow numerical models(Braun et al.,1990b, Chupp et al.,1991b). While the basic premise of the model is similar to that advanced by Braun et al.(1990b) and Hendricks et al.(1991b), the only parameters considered is the effective brush thickness. The authors showed that the single parameter model has the capability to predict pressure drops and temperature rises, when compared to experimental data generated by Teledyne CAE and Allison.

II SCOPE OF THE PRESENT WORK

Conclusions of a recent workshop(Liang, Edit., 1991) indicate that while the brush seals works well, there is a need to improve its performance characteristics. Such a goal can be achieved by using cascades of brushes, nonhomogeneous brush morphology, "non-conventional" brush structure design(Hendricks, 1992), and in general, a process of optimization of brush design parameters(Gerin, 1991). The concept employed by the distributed bulk flow numerical models(Braun et al.,1990b, Hendricks et al.,1991b, Chupp et al.,1991b) can not predict local brush compliance, and the associated local flow and pressure drop phenomena. Neither can the empirical formulas used for the pressure drops in array of tubes of Zukauskas(1988). The importance of the local flow phenomena in the sealing process is paramount to the global performance of the brush(Braun et al., 1990a, 1991b, 1992, Hendricks et al., 1991a).

The distributed flow fields velocities(\(u, v\)) and the
associated pressure maps are of vital importance for the prediction of the average pressure drop, or the possible sudden failure of the brush seal under unexpected local "pressure hikes". The momentum carried by these velocities (or the upstream pressure) can force brush deformation (compliance), and can create favorable conditions for the brush "opening" (Braun et al., 1991b) followed by subsequent seal failure.

It is in this context that the development and validation of a numerical model with distributed primary parameters (u, v, p) becomes important. The numerical model is a two dimensional time dependent formulation of the Navier-Stokes equations, constant properties, and includes the effects of inertia, viscous and pressure terms. The algorithm is applied to a set of non-compliant multirow, multicolunm pin configurations that are similar to the ones found in an idealized brush seal configuration. The numerical parametric investigation aims to establish the occurrence of major flow patterns and associated pressure maps that characterize the geometry under study. The experimental portion of the paper is aimed at gaining further insight into the relevant flow structures, and thus guide the development of the mathematical and numerical model to qualitative and quantitative coincidence with the experiment.

III DEVELOPMENT OF THE ANALYTICAL AND NUMERICAL MODEL.

"Unexpected" local recirculation, reverse and lateral flows between the rows of the brush, or downstream of the brush zone, appear to play a major role in the sealing process effected by the brush. What's more, the compliance of the brush body, has an ever changing geometry during operation and requires continuous prediction of the bristles’ position.

Most of the aforementioned characteristics can not be incorporated within the context of a porous medium model. Its major attractions represent, at the same time, its fundamental weaknesses: (i) the intrinsic concept of rigidity, and (ii) the inability to model the recirculating, multidimensional flow zones. A distributed model however, can accommodate successfully all of the above mentioned features.

Mathematical Model.

The operating environment of a brush seal will generate component flows that are mainly directed (i) normally to the free stream velocity U_0. Taking the divergence of the X- and Y-momentum equations, and using continuity for simplification, one obtains a pressure equation that appears under a Poisson type format.

\[ \nabla^2 P = \frac{\partial^2(U^2)}{\partial X^2} - 2 \frac{\partial^2(UV)}{\partial X \partial Y} - \frac{\partial^2(V^2)}{\partial Y^2} + \left( \frac{\partial^2(U)}{\partial X^2} + \frac{\partial^2(U)}{\partial Y^2} \right) \frac{Re}{2} \frac{\partial^2(U)}{\partial X^2} + \frac{\partial^2(U)}{\partial Y^2} \]

where \( \partial \) is the dilatation term \( \partial = \frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} \). One can see that \( \partial \) represents the continuity equation and implicitly, during calculations, represents the residual that has to become identical zero if the continuity is to be satisfied. This is a necessary but not sufficient condition for the convergence of pressures in Eq. 4.

Boundary and Initial Conditions.

The Momentum Equation. The boundary conditions on the lateral solid walls assume non-slip conditions and non-porous walls. At the pin array entrance the velocity is assumed to be uniform with \( \bar{U}=1, \bar{V}=0 \) (angle of incidence is zero). A reference pressure is assigned to one point on the inflow boundary. At the exit, the flow is allowed to develop naturally with the boundary conditions for velocities derived from the satisfaction of the continuity equation.

\[ \frac{\partial U}{\partial X} = \frac{\partial V}{\partial Y} = 0 \quad \text{at } X=0;X=L; \quad \text{and } 0<Y<h \]

Boundary Conditions for the Poisson’s Equation. The dynamic pressures on the inflow and outflow boundaries are allowed to float and were determined through the balance of the normal forces with the inertia and viscous forces. The effects of the terms \( \frac{\partial^2(U)}{\partial X^2} \) and \( \frac{\partial^2(U)}{\partial Y^2} \) both at inflow and outflow have been considered negligible. Thus one obtains

\[ \frac{\partial P}{\partial X} = \frac{1}{\text{Re} \cdot \text{Eu}} \left( \frac{\partial(U)}{\partial X} + \frac{\partial(U)}{\partial Y} \right) + \frac{1}{\text{Re} \cdot \text{Eu}} \frac{\partial^2(U)}{\partial X^2} + \frac{\partial^2(U)}{\partial Y^2} \]

at \( X=0;X=L; \quad 0<Y<h \) (6)

Boundary conditions of the non-contiguous internal boundaries of the pins, in addition to Eq. 6, one needs to add an expression for \( \frac{\partial P}{\partial Y} \) and

\[ \frac{\partial P}{\partial Y} = \frac{1}{\text{Re} \cdot \text{Eu}} \left( \frac{\partial(V)}{\partial X} + \frac{\partial(V)}{\partial Y} \right) + \frac{1}{\text{Re} \cdot \text{Eu}} \frac{\partial^2(V)}{\partial X^2} + \frac{\partial^2(V)}{\partial Y^2} \]

This formulation is totally independent of the internal boundary configuration.

At the channel’s upper and lower walls the pressure boundary condition takes a simplified form due to the fact that \( U=V=0 \).

\[ \frac{\partial P}{\partial Y} = \frac{1}{\text{Re} \cdot \text{Eu}} \frac{\partial^2(V)}{\partial Y^2} \quad \text{at } Y=0; \quad Y=h; \quad 0<X<L \]

Initial conditions (T=0). The velocities are given as \( U=1; \quad V=0 \). The pressures are set initially to \( P=P_{ref}=\text{const} \).

Numerical Implementation and Solution Procedure.

The finite difference method applied here uses a collocated constant size grid throughout the entire domain. The geometric details of the grid and the layout of the array of pins are shown in Fig. 1B. The discretization of the system of governing equations follows through the use of the alternate direction method (ADI). The procedure uses the full direct approximation of each term within the differential equation on every half time step, \( \Delta \tau/2 \). One obtains the following system of linear algebraic equations.

\[ \frac{u^{n+1/2}-u^n}{\Delta \tau/2} = \frac{1}{\text{Re}} \left( \Lambda_{xx}(u)u^{n+1/2} + \Lambda_{yy}(u)u^n \right) + c_u(u)^n \frac{n+1/2}{c_x(u)^n + Q(u)^n} \]
The pressure boundary conditions represented by Eqs. 6, 7, can be written in operator finite difference form as
\[ \frac{p_{s+1/2,n+1}}{\delta p} - \frac{p_{s,n+1}}{\delta p} = \frac{\Delta xx(p)_{s+1/2,n+1}}{\delta x} + \frac{\Delta yy(p)_{s,n+1}}{\delta y} \]

while that of Eq. 8 takes the form of
\[ \frac{p_{s+1,n+1}}{\delta p} - \frac{p_{s+1/2,n+1}}{\delta p} = \frac{\Delta xx(p)_{s+1/2,n+1}}{\delta x} + \frac{\Delta yy(p)_{s,n+1}}{\delta y} \]
experimental and the numerical results show a good coincidence for the flow patterns, the size of the recirculation and the position of the vortex center with respect to the moving cylinder.

V RESULTS AND DISCUSSION.

Numerical Results(PTDR=1)

There is a wide body of numerical work treating the flow around a circular cylinder in crossflow(Kawamura et al., 1986, Fornberg, 1980, Ohya et al., 1992, Li et al., 1992). However, few researchers focused their attention on the nature of the flow changes when it interacts with a bank of tubes(Reynell, 1991). The effects of the cylinders' arrangement and the array size on the flow structure are presently not fully understood, especially when the pitch-to-diameter-ratio(PTDR) is very small(<<1).

Flow and Pressure Patterns. Figure 3A presents the flow, at Re =2000, for a staggered array of six rows of tubes with a PTDR = PTDR =1. The flow enters the cross section with a symmetric velocity distribution, which completely changes its structure upon passing through the first row of tubes. One can notice the characteristic jetting between the pins, and the formation of recirculation zones in the wake of the pins. The nature of the PTDR does not allow the growth of the recirculation zones and forces their closure within one pin diameter. In the wake of the last row of pins one can notice the shedding of eddies as well as the formation of steady recirculation zones. The computed non-dimensional pressure drop was 28.8. Figure 3B and 3C present for the same Reynolds number and non-dimensional time(T=0.14), the flow patterns between a cascade of two formations of pins(A and B) of three rows of pins each. The feature that differences them is the spacing (C) between the two formations of pins(C=3d and C=5d respectively). The recirculation zones between A and B, Fig. 3B, occupy longitudinally the entire space C, while laterally they are limited by the rivering jets to one width diameter. The jets exhibit no expansion in their width. The wake behind the last rows of pins is qualitatively similar to the one of Fig. 3A, even though its length has increased, and shows diminished shedding. The computed pressure drop was 29.08. The larger C distance between the the two formations of pins of Fig. 3C allows the closure of the wake at approximately three diameters behind zone A. These occurrence gives the jets the opportunity to expand and merge all along the cross section, only to re-accelerate upon entering the first row of pins of zone B. This phenomenon is associated with an additional expenditure of mechanical work that causes an increase in the pressure drop (computed) to 31.53. This effect, can be crucial for design of more effective brush seal configurations.

Figures 4A and 4B present the development of flow in an array of 7(rows)x11 round pins with a PTDR = PTDR =1. In Fig. 4A, Re =100, while in Fig. 4B, Re =2000. The same basic flow patterns of Fig. 3, are visible. The wall jets effects are more visible since the last row contains 11 pins rather than the 10 pins of Fig. 3. The flow patterns in the regions marked in Figs. 4A and 4B are shown in detail in Figs. 4C and 4D, respectively. One can see the lack of recirculation in the wake of the pins for Re =100 in Fig. 4C, while for Re =2000, the formation of two standing vortices is clearly displayed. The size and early closure of the wake is consistent with the results shown in Fig. 3.

Figure 5 presents the calculated pressure field for the two cases considered in Fig. 4. Figure 5A presents the pressure distribution for the case of Re =100. The non-dimensional pressure drop is 67.3. As the Reynolds number is increased to 2000, the pressure drop decreases to 33.3. One should keep in mind that the pressure non-dimensionalization follows as P=p/pUo, with Uo varying directly proportional with the Reynolds number. The same wavy pattern of pressure drops was reported by Braun et al. (1991a, 1991b). It is apparent that every two rows act as a stage in a cascade of individually laced brushes.

Figures 6 presents calculated pressure profiles in front and
FIG. 3 FLOW ACROSS ARRAY OF PINS AT \(Re = 2000\), \(PTDR_{t} = 1\), \(PTDR_{b} = 1\) A) SIX ROWS; B) CASCADE OF TWO ELEMENTS (THREE ROWS EACH), \(C = 3d\); C) CASCADE OF TWO ELEMENTS (THREE ROWS EACH), \(C = 5d\).

FIG. 4 FLOW THROUGH BASIC ARRAY CONFIGURATION 7 ROWS X 11 PINS. A) \(Re = 100\); B) \(Re = 2000\); C) DETAIL OF FLOW IN THE QUADRANT INDICATED IN FIG. 4A; D) DETAIL OF FLOW IN THE QUADRANT INDICATED IN FIG. 4B

in the wake of each one of the rows of pins. Figures 6A and 6B present the pressure variations at \(Re = 100\). Analysis of these two images indicates that the drop in pressure occurring at the leading edge of any given row is followed by a pressure recovery in the wake of the row, only to be followed by a renewed drop in pressure as the fluid enters the next row of pins. The same phenomenon occurs at \(Re = 2000\) in Figs. 6C and 6D. However, in this case the pressure recovery is minimal. The phenomenon exhibited by these numerical experiments sheds light on a mechanism of kinetic energy consumption believed to be instrumental in the sealing process.

Figures 7 shows the effect (decrease) of the \(PTDR_{t}\) on the structure of the flow patterns. The numerical experiments were
performed at Reₜ = 2000 for PTDR                                                                              =1(Fig. 7A), 0.66(Fig. 7C),  and 0.33(Fig. 7E) respectively. The decrease in the PTDR  engenders a contraction, and even complete disappearance(Fig. 7E) of the recirculation zones behind the pins of the inner cylinders(bold contours), while exerting little influence on the size or shape of the wakes behind the last row of cylinders. A close view at the physical nature of the wakes shrinkage is detailed in Figs. 7B, 7D and 7F. The fluctuations of the pressure drops associated with the events of Figs. 7, can be studied in Table 5, Part A. Part B shows the pressure drops in the same array of pins for Reₜ = 100. The pressure drops show a consistent increase with the decrease in the PTDR  . At low Reₜ , the lack of the recirculation zones eliminates one mechanism responsible for the pressure drops at high Reynolds number(Reₜ = 2000), and leaves friction and fluid acceleration as the only responsible mechanisms.

Effect of the Numerical Scheme. To ascertain the physical veracity of the results, the first order upwind scheme used for the present analysis has been compared with the third order deferred correction scheme(Kudriavtsev, 1991, Hayase at al. 1992). The comparison covers a range of Reₜ between 500 and 2000. The flow patterns observed in-between the pins and in the wake of the array were practically identical for the two methods. The comparison of the corresponding pressure drops yielded by the two schemes has been found to be within a 4% envelope,
FIG. 7 VARIATION OF THE FLOW FIELD STRUCTURE WITH THE CHANGE IN THE LONGITUDINAL PITCH.

**TABLE 4.**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Upwind</th>
<th>Third-order PUI DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re=500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta P_{\text{Row}}$</td>
<td>38.54</td>
<td>40.19</td>
</tr>
<tr>
<td>$\Delta P_{\text{out}}$</td>
<td>36.81</td>
<td>35.63</td>
</tr>
<tr>
<td>Re=1000</td>
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<td></td>
</tr>
<tr>
<td>$\Delta P_{\text{Row}}$</td>
<td>36.21</td>
<td>37.83</td>
</tr>
<tr>
<td>$\Delta P_{\text{out}}$</td>
<td>34.31</td>
<td>36.07</td>
</tr>
<tr>
<td>Re=2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta P_{\text{Row}}$</td>
<td>35.13</td>
<td>36.42</td>
</tr>
<tr>
<td>$\Delta P_{\text{out}}$</td>
<td>33.25</td>
<td>34.64</td>
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</tbody>
</table>

**TABLE 5**

<table>
<thead>
<tr>
<th>Part A</th>
<th>Re=2000</th>
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<tr>
<td>PTDR$_L$</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>35.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part B</th>
<th>Re=100</th>
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<tbody>
<tr>
<td>PTDR$_L$</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>67.3</td>
</tr>
</tbody>
</table>

**TABLE 6.** Temp. $T=70^\circ F$, $\rho=950$kg/m$^3$. Fluid velocities: $U=18.5$ cm/s ($Re_h=195$), $U=31$ cm/s ($Re_h=327$).

<table>
<thead>
<tr>
<th>$Re_h$</th>
<th>$\Delta P$(psi)</th>
<th>$\Delta P$(Pa)</th>
<th>$u_h^+$</th>
<th>$\Delta P$( nondim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>195 (exp)</td>
<td>4.92</td>
<td>27,758</td>
<td>32.16</td>
<td>863</td>
</tr>
<tr>
<td>195 (num)</td>
<td>4.31 ($\pm7%$)</td>
<td>926</td>
<td></td>
<td></td>
</tr>
<tr>
<td>327 (exp)</td>
<td>6.82</td>
<td>47,656</td>
<td>91.29</td>
<td>516</td>
</tr>
<tr>
<td>327 (num)</td>
<td>8.6 ($\pm26%$)</td>
<td>650</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6. One can conclude that the amount of artificial viscosity introduced by the conservative first order upwind scheme does not deteriorate the truthfulness of the solution within the Reynolds range considered in this paper.

Experimental Results (PTDR, PTDR_{T}<0.1)

The experiments were conducted in a test facility that is briefly described in Appendix A.

Figure 8 presents qualitatively the flow in the wake of a 3(rows)x11 array, at Re_{h}=197(Fig. 8A), Re_{h}=500(Fig. 8B), and Re_{h}=956(Fig. 8C). In Fig. 8A the exiting jets have a coherent structure interrupted by small recirculation zones behind the pins, Fig. 9A. These zones close within 1/2 pin diameter and do not influence either the jets development or the unimpeded flow of mass through the array. As Re_{h} increases to 500(Fig. 8B), and 956(Fig. 8C), the flow changes visibly its structure, and one can now observe a non-symmetry situation between the flow near the upper wall, and the one near the lower wall. These structures are due to non-equal pitches between the upper wall and pin 1 and the lower wall and pin 11, respectively. Details of the local flow structures between pin 1 and the upper wall are shown in Figs. 9B and 9C. The strong jet flowing adjacent to the upper wall, generates a low pressures zone that molds the S shaped jet emerging from pins 2 and 3, and the associated vortex zones. Note that even though the increase in the Re_{h} changes the content of the vortex structures, the area occupied remains unchanged. A further increase in the Re_{h} to 956 develops two recirculation zones of butterfly-like structure that are symmetric with respect to pin 6. The zone behind the upper four pins develops the structure shown in Fig. 9C. The low pressure region engendered by the wall jet becomes dominant across the entire section, and the jets emerging from the spaces between the pins deviate towards the zones of lower pressure. This situation is instrumental in creating both the structure of Fig. 9C, and the butterfly effect which can be seen in detail in Fig. 10. One notices the structure of the upper half of the butterfly as it is confined by the jet emerging from in-between the pins(zone A, Fig. 8). A similar flow formation was also reported in experiments performed by Zdravkovich et al.(1988). The butterfly which appears due to an interplay of transversal low pressure zones and longitudinal pressure inversions has the net effect of 'sealing' the exit of the array, thus preventing the flow from 'leaking' downstream.

Comparison of Some Experimental and Numerical Results (PTDR_{T}, PTDR_{T}<0.1). The magnitude and trends of the pressure drops across the array is a very important parameter in the determination of the sealing effectiveness. The authors compared the measured pressure drops with their numerical counterparts. The physical configuration involved was identical to the one described in the section above, and Appendix A. The results are detailed in Table 6. For Re_{h}=195 one can observe a difference of only 7% between the numerical and experimental results. As the Re_{h} increase to 327 this good coincidence deteriorates. The result can be mitigated through the consideration of the error introduced by the scaling factor \rho U_0. As the Reynolds number increases the velocity U_0 increases. An estimated error of 5% in the measurement of U_0 propagates proportional with U_0. The table presents the change in the fluid velocities for the two cases analyzed.

Figure 11 presents the flow pattern in the array of three rows discussed above when Re_{h}=195. This allows direct comparison between this figure and the experimental results presented in Fig. 8A and 9A. Figure 11A models the same geometric asymmetry mentioned in the discussion of Figs. 8 and 9. The effect of this asymmetry is evident in the upward deviation of the inlet flow of Fig. 11A. Experimental observation confirmed the same trend for the inlet flow as the one reproduced numerically. In the exit section of the array, a comparison of Fig. 11A and 8A shows good qualitative coincidence. One can see that the inlet flow asymmetry carries through, and in both
VI CONCLUSIONS

This paper presents an analysis and numerical simulation for flow in an array of pins with a PTDR varying between 1 and 1. The effects of the Reynolds number variation and array configuration have been studied. The experimentally obtained results concerning the jet riveting between the pins, and the formations of recirculation zones in-between cascades of pins have been confirmed numerically. It was found that the distance (zone C, Fig. 3) between zones of densely packed pins can be influential on the overall pressure drop. Contrary to expectations, an increase in zone C length can carry with it quite a substantial increase in the pressure drop. This phenomenon has been attributed to the nature of the development of the recirculation zones in zone C. The interplay of successive pressure drops and partial pressure recovery, Fig. 8, inside the array of tubes has also been found to contribute greatly to the overall pressure drops across the array of pins. Finally, the experimental results shown in Figs. 8, 9, and 10, indicate the apparition of the large recirculation zones in the wake of the array of pins which are associated with longitudinal and cross sectional pressure inversions that contribute to the sealing effect.

VII REFERENCES

FIG. 11 COMPARISON OF NUMERICAL AND EXPERIMENTAL FLOW PATTERNS AT \( \text{Re}_h = 195 \)


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APPENDIX A.

Description of the Test Facility.

The test facility, Fig. 1A comprises four parts: the oil tunnel with the test section, the laser assembly and appropriate optical lenses, the low luminosity TV camera with a modified front-end long distance microscope, and the computer based image processing system. We shall describe briefly below the major aspects of the system. For the interested reader a full description of the system and the experimental procedure are given by Braun et al.(1992, 1990a,b, 1991a,b).

The Oil Tunnel. This facility is designed to study the behavior of one or more brushes in a pump pressurized environment at higher flow velocities. The tunnel is manufactured contains a lucite wall test section that is 333mm(lft) long and 25.4mm(1in) thick. The tunnel is 1524mm(5ft) long with a square cross section of 76.2mm x 76.2mm(3in. x 3in). The test section contains a breadboard on which pins can be mounted in any arbitrary configuration. The board has pins that are 0.250in diameter and are spaced at S =0.020 in and S =0.020 in for a pitch to diameter ratio of PTDR =PTDR =0.08.

The Image Vision System and Data Processing. The full television based imaging system, not shown in the figure, has an identical configuration to the one described in references(Braun et al., 1990a,b, 1991a,a). The TV camera is positioned at 90deg, with respect to the plane of light. The plane of the laser light sheet is parallel with the main direction of the flow stream, Fig. 1A. The basic idea for flow visualization involves the shining of a planar laser sheet of light through the region of interest in pins array to make visible the magnesium oxide seed particles that trace the fluid flow. The recorded images are subsequently processed to yield qualitative and quantitative information about the nature of the flow.

FIG. 1A. TWO-DIMENSIONAL FLOW VISUALIZATION OIL TUNNEL