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Flows in Pinned Arrays Simulating Brush Seals

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ERRATA

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Page 2, equation (3) should be replaced with

$$\begin{aligned} \varepsilon &= \mathrm{Vopen} / \mathrm{Vtotal} = 1 - \mathrm{Vs} / \mathrm{Vt} \\ &= 1 - \pi \mathrm{No}\, d^2 / \left(2(1 + \mathrm{do}/\mathrm{di})\langle t \rangle \cos(\theta + \varphi)\right) \end{aligned} \tag{3}$$

Page 13, Figure 10 should be replaced with

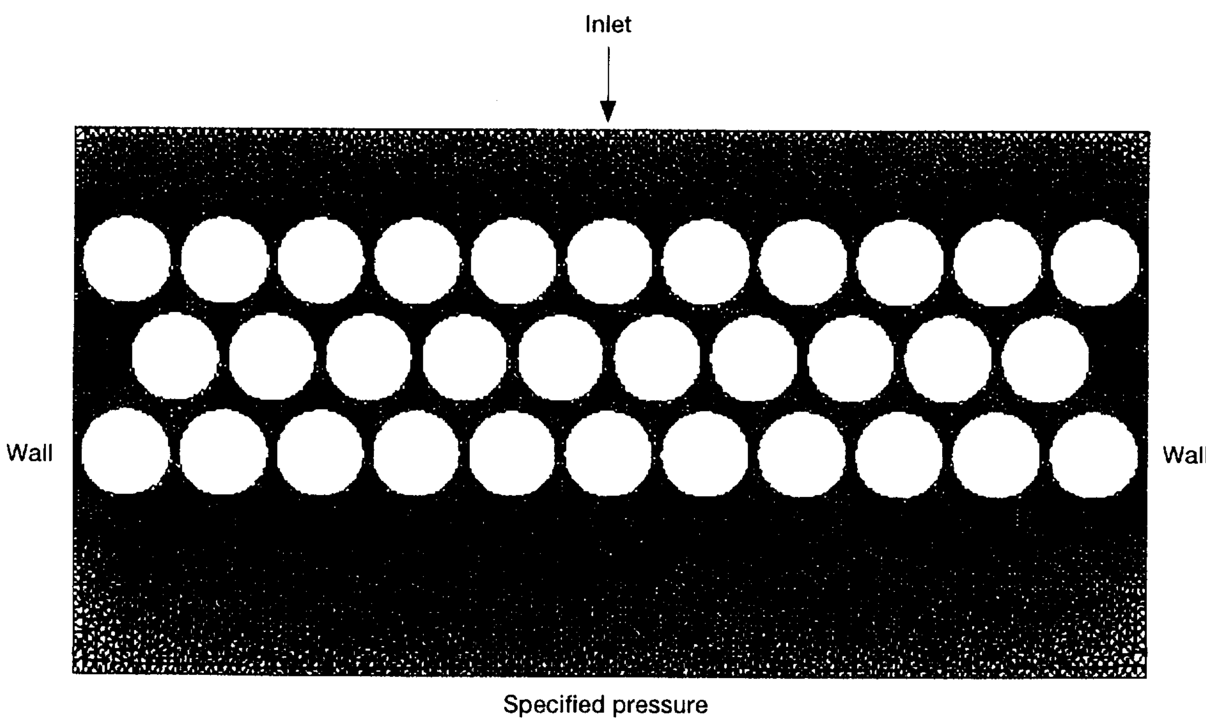

Figure 10.—Grid and boundary conditions for anisotropic pin array of reference 7, ref (9).

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SUMMARY

Flows through idealized pin arrays were investiagted using a quadrilateral grid finite element model and the simplified Ergun model to predict leakage flows and pressure drops in brush seals. The models are in good agreement in the laminar region with departures in the laminar-turbulent transition region as defined by the simplified Ergun model. No local disturbances in the velocity or pressure fields, symptomatic of turbulence were found in the numerical results. The simplified model failed to predict the pressure drop of a 32-pin anisotropic array unless the gap is taken as the smaller of the anisotropic gaps. Transitional and anisotropic behavior requires further investigation.

NOMENCLATURE

A	flow area without bristles (pins)
Dp	hydraulic diameter = 1.5 d
d	bristle (pin) diameter
di	shaft diameter
do	fence diameter
Go	mass flux without bristles (pins)
go	gap between bristles (pins)
No	number of bristles (pins) per cm of circumference
N_θ	number of bristles (pins) in a row (circumferential)
Nx	number of bristle (pin) rows
Re	Reynolds number
ΔP	pressure drop
<t>	bristle pack thickness
$\dot{w}$	mass flow rate
$\dot{V}$	velocity
ε	porosity
ρ	density
μ	viscosity (dynamic)
ν	viscosity (kinematic)

Subscripts

s solid
t total

INTRODUCTION

Brush seals are effective, compliant, contact seals. Over their lifetime, these seals are subjected to considerable wear, bristle displacement, high pressure drops and thermal loads along with unusual operating conditions and hystersis. These limitations were recognized by Fergeson (ref. 1) yet he successfully implemented brush seals as replacements for some labyrinth seals in gas turbine engines. Other researchers investigated the geometric effects e.g., fence height, clearance (Gorelov et al. (ref. 2)), while others concentrated on understanding the nature of brush flows (Braun et al. (ref. 3)) and predicting flows as a function of pressure drop (Chupp(4)). Brush seal flows are complex and three dimensional with a variety of patterns recognized, figure 1. The porous fiber bulk flow model (Hendricks et al. (ref. 5)) include the effects of bristle motion and provides a value of direct dynamic stiffness. Brush seal rotordyanmics coefficients have been assessed by Childs et al. (ref. 6). Preliminary CFD modeling and validation have been completed by Kudriavtsev (refs. 7 and 8) and Athavale (ref. 9). Unfortunately, both these efforts have been delayed.

Kudriavtsev and Braun (ref. 7) validated their CFD code using 2-D arrays of pin-cylinders. The agreement between experiment and theory is good, figure 2, including simulation of turbine vane cooling. Expanding the CFD code to include flow within the cavity and a porous media model of the brush, brush sealing in a gas turbine engine was simulated, figure 3, but not validated (ref. 8).

In Athavale's approach(9), the effect of heating and the 3-D bristle geometry was calculated illustrating that bristles isolated by rivering flows can be starved for coolant and produce non uniform heating at the interface, figure 4. Such heating produces nonuniform wear of the bristles and decreases the effectiveness of the brush seal.

The extension of the Ergun porous flow model (ref. 10) to brush seal flow data provides reasonably good results for gases, reference 11.

Herein we continue to expand porous flow simulation models for brush sealing by comparing preliminary results for flows as computed using CFD modeling.

BULK FLOW MODELING

The simplified Ergun model of flows in porous media, reference 11, provides useful dimensionless forms and insights into design parameters:

$$\psi = \Delta P\bar{\rho}(1.5d)\,\varepsilon^3/(1-\varepsilon)\langle t\rangle G_0^2$$
$$= 150/\big(\mathrm{Re}_1/(1-\varepsilon)\big) + 1.75 \qquad (1)$$

$$\mathrm{Re}_1 = 1.5\,\mathrm{God}/\mu;\ \mathrm{Go} = \rho_o\dot{V} = \dot{w}/A$$

$$A = \pi\left(d_o^2 - d_i^2\right)/4;\ \mathrm{Dp} = 1.5d \qquad (2)$$

$$= \mathrm{Vopen}/\mathrm{Vtotal} = 1 - \mathrm{Vs}/\mathrm{Vt} \qquad (3)$$

$$= 1 - \pi\mathrm{No}\,d^2/\big(2(1+\mathrm{do}/\mathrm{di})\langle t\rangle\cos(\theta+\varphi)\big)$$

and the upper bound on the thickness and number of rows becomes

$$\langle t\rangle = d\,\mathrm{Nx} = d\,\mathrm{di}\,\mathrm{No}/N_\theta \qquad (4)$$

where No is the number of bristles per unit length as provided by the manufacturer or by micro-examination of the brush interface.

The values of ψ and $Re_1/(1-\varepsilon)$ are calculated from the data set of Carlile et al. (ref. 12), for gases helium, air and carbon-dioxide, and overplotted on the results presented by Ergun (ref. 10) as illustrated in figure 5.

These results are promising and warrent development of a numerical model to extend the range of validity of a porous model.

NUMERICAL MODELING

In the ideal case of an array of cylinders in cross flow, symmetry allows considerable simplification and only a segement of the array need be modeled and calculated. A 6701 quadrilateral finite element grid was constructed with grid concentrations within the gaps. Periodic boundary conditions were applied to the inlet and outlet velocity using a slug profile to calculate an exit profile that becomes the inlet velocity, with symmetry along the parting planes and no slip conditions at the solid interfaces. The grid model and dimensionless boundary conditions for the FEM-flow solver, are illustrated in figure 6. The flow field is considered laminar. The dimensionless parameters are defined as (refs. 7 and 8):

$$Re_2 = \left(\frac{\dot{V}d}{go}\right)\left(\frac{d}{\mu}\right)$$

$$P = P\left(\rho\left(\dot{V}d/go\right)^2\right) \tag{5}$$

where $\dot{V} = \dot{w}/(\rho\, A)$, go = g1 = g2 represents the gap at the inlet and exit boundaries, d is the bristle diameter, ρ the density, and μ the dynamic viscosity. In this simulation, the pressure drop across Nx bristle rows is assumed to be linear and the porosity can be determined by

$$\varepsilon = 1 - Vs/Vt = 1 - \pi/\left(2\sqrt{3}\left(1 + go/d\right)^2\right) \tag{6}$$

Where Vs is the total solid, Vt the total volume, and go, the spacing between the bristles and ε the porosity. Selected values of (d/go) are 14, 28, and 35 and characterize typical brush configurations. No effect of pressure differential on the bristle, motion of the interface, or elliptical nature of the flow about the bristle or details of the complex 3-D flow characterizing a brush are condsidered in this model.

RESULTS

In the simulation, the Reynolds number (Re_2) was varied over a range of 10 to about 400 for each of the three (d/go) values (14, 28, 35) and the pressure drop calculated. These computed pressure drops are given as Table 1, and plotted on figure 7 along with the simple Ergun model predictions as a function of maximum gap flow velocity. The differences between the results as computed using the ALGOR FEM solver and CFD-ACE FD solver were within 1 to 2 percent.

The difference between the FEM predictions and the simple model become pronounced at maximum gap velocities above 25 m/s indicating a departure of the modeling methods. While local circulation or turbulence are the most likely contributors, considerable attention was given to the computed flow field and not disturbances were found over this range in Reynolds numbers, figure 8; the pressure contours are also quite smooth, figure 9. It is true, that the FEM model did not admit turbulence and the first-order upwinding scheme may have excessive artificial viscosity to prevent circulation; however prior computation experience, references 7 and 8, does not show effects of turbulence for the Reynolds number range of Table 1 and little 2-order upwinding effects. For closely packed cylinders (g/d > 20) viscous effects are very strong due to the walls proximity and flow surface to wetted perimeter ratio. Recirculations appear only for Re > 1200 and were corroborated by both ALGOL and CFD-ACE using both first and second order convective schemes.

To illustrate the potential departure from laminar flows, the FEM model results are plotted in terms of the Ergun model as figure 5. The three parametric lines (d/go = 14, 28, 35) closely parallel the Blake-Koseny relation representing laminar flows in porous media up to Reynolds numbers (Re_1) of 15 where the effects of turbulence or equivalent disturbances cause an increase in the pressure drop for a specific Reynolds number; this corresponds to a maximum computed velocity in the gap of about 20 m/s. These differences remain to be studied.

In further efforts do determine the relations between the simple Ergun model and computational results, in the first case, a set of pin arrays as presented in references 7 and 8 were modeled, figure 10. The array has 3 columns of 11, 10, and 11 pins respectively that are spaced (d + go) both axial and transverse giving an anisotropic gap (g1 = g2) spacing and flow field. The simplified model was applied, but underpredicted the pressure drop by nearly a factor of 3, see figure 5, even though the CFD codes of Athavale (ref. 9) and Kudriavtsev and Braun (refs. 7 and 8) both predict the experimental data. In the second case, the transverse (d/g1) was set to 35 and the longitudinal (d/g2) was set to 51. The results, Table 1 and figure 5, show a nearly 2:1 departure from the simplified Ergun model. The reason for failure of the simple model is being investigated.

Anisotropic Bristle Spacings

To this point, using the standard definitions for bristle spacings, correlation of flows in anisotropic bristle spaced configurations have been unsuccessful. Redefinition of the void fraction in terms of both the g1 (transverse or normal to the flow) and g2 (longitudnal or in the flow direction) spacings.

$$
\begin{aligned}
\varepsilon - 1 &= (\pi/4)/\big((1 + g1/d)(1 + g2/d)\cos(\varphi)\big) \\
\varphi &= \arcsin\big((1 + g1/d)/(2(1 + g2/d))\big)
\end{aligned}
\tag{7}
$$

did not correlate the results.

Due to flow symmetry it was reasoned that flow rates would be controlled by g2, if g2 < g1, and vice versa for g2 > g1. However, the control is simply assuming a symmetric geometry letting go be the lesser of g1 or g2 with porosity defined as equation (6).

For the case of d/g1 = 35 and d/g2 =51, the assumed equivalent symmetric geometry is d/go = 51. The resulting locus becomes parallel to that noted on figure 5, except shifted through the point ($Re_1/(1 - \varepsilon) = 3.7$ and $\psi = 42$). The estimated pressure drop becomes 5.1 psi with the numerical estimate at 6.1 psi.

Using this same geometric reduction for the oil data of Braun (1993) (ref. 7 and fig. 5), the estimated pressure drop becomes 4.1 psi and the experimental pressure drop is 4 psi.

Entrance Effects

Other considerations include the study of flows within in-line tube banks (Athavale, 1995), which showed that for laminar flows up to 7 tubes row were necessary for establishing uniform flows and up to 20 for turbulent flows. For laminar flows the pressure coefficient diminished monotonically and has a minimum for the turbulent cases. Further, some jetting characterized the flow field where the fluid traveled umimpeded up to seven tube rows. A similarity between this finding and those for closely spaced orifices in noted where jetting is strongly dependent on thermophysical properties, the number of orifices, and their spacing (Hendricks, 1982).

These results suggest the complexities associated with flows in similar but geometrically simple configurations compared to brush seals, are yet to be understood with any great detail. Further without the simplification of symmetry, the computations become excessive. The simplified model certainly has many limitations yet it provides the designer with first order values for anticipated flows and pressure drops.

CONCLUSIONS

The prediction of pressure drop across an idealized array of pins for a fixed diameter/spacing ratio show good agreement with the simplified Ergun model in the laminar regime.

Departures that occur are indicative of turbulent effects according to the simple model, but careful investigation of the computed velocity and pressure fields appear void of perturbations that are indicative of turbulent behavior.

The simplified model fails to predict, by a factor of 3, the pressure drops associated with both the numerical and the experimental results of a 32 pin anisotropic array and by nearly a factor of 2 for an anisotropic array characterized herein. However, if the geometric configuration were assumed symmetric where go is the smaller of g1 or g2 with porosity defined as equation (6), then a better resolution is provided for the experimental data (Braun, 1993) and the numerical results herein.

The departures of the model due to anisotropic behavior, local circulation and transition to turbulence remain to be explored.

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Table 1. Parametric results for FEM-model and simplified Ergun model.

Simplified Ergun Model [Re/(1 - ε), ψ]

	Vmax,m/s	1/Re	Re	P (in)	P(out)	Delta P	ro*V**2	DP, Pa	DP, psi	psi		
gap, 1/28	4.803922	0.1	10	210	-3.56	213.56	38.5397	8230.538	1.196473	1.14	2.74	59
	9.607843	0.05	20	105.37	-1.616	106.986	154.1588	16492.83	2.397562	2.36	5.48	29.6
d=5.1e-5m	12.0098	0.04	25	84.3	-1.23	85.53	240.8731	20601.88	2.994894	3.	6.85	23.7
	19.21569	0.025	40	52.7	-0.65	53.35	616.6351	32897.48	4.782306	5.	11.	14.7
	32.02614	0.015	66.66667	31.64	-0.28	31.92	1712.875	54674.98	7.9481	9.	18.3	8.8
	48.03922	0.01	100	21.1	-0.192	21.292	3853.97	82058.72	11.92887	14.6	27.4	5.9
	188.3891	0.00255	392.1569	5.435	-0.0636	5.4986	59269.04	325896.8	47.3756	98	108.	1.5
choked	320.2614	0.0015	666.6667	2.739	-0.032	2.771	171287.5	474637.8	68.99808			
23												
	Vmax,m/s	1/Re	Re	P (in)	P(out)	Delta P	ro*V**2	DP, Pa	DP, psi			
gap, 1/14d	4.803922	0.1	10	76.83	-2.46	79.29	38.5397	3055.813	0.444223	0.55	4	31.8
	9.607843	0.05	20	38.42	-1.18	39.6	154.1588	6104.688	0.887438	1.15	8	15.8
	12.0098	0.04	25	30.74	-0.931	31.671	240.8731	7628.692	1.108983	1.47	10	12.7
	16.01307	0.03	33.33333	23.06	-0.674	23.734	428.2188	10163.35	1.477445	2.	13.3	9.6
	19.21569	0.025	40	19.22	-0.545	19.765	616.6351	12187.79	1.771739	2.5	15.9	7.9
	32.02614	0.015	66.66667	11.55	-0.289	11.839	1712.875	20278.73	2.947919	4.6	26.6	4.7
	48.03922	0.01	100	7.72	-0.192	7.912	3853.97	30492.61	4.432709	7.7	39.8	3.2
	188.3891	0.00255	392.1569	2.079	-0.0356	2.1146	59269.04	125330.3	18.21926	58.3	156	0.85
choked	320.2614	0.0015	666.6667	1.542	-0.0226	1.5646	171287.5	267996.5	38.95864			
	Vmax,m/s	1/Re	Re	P (in)	P(out)	Delta P	ro*V**2	DP, Pa	DP, psi			
gap,1/35	4.803922	0.1	10	287.838	-5.904	293.742	38.5397	11320.73	1.645694	1.38	2.5	68.5
	9.607843	0.05	20	143.92	-2.9154	146.8354	154.1588	22635.97	3.29059	2.84	5	37.1
	12.0098	0.04	25	115.139	-2.317	117.456	240.8731	28291.89	4.112806	3.6	6.25	26.5
	16.01307	0.03	33.33333	83.357	-1.719	85.076	428.2188	36431.15	5.295995	4.9	8.4	21.3
	19.21569	0.025	40	71.956	-1.4206	73.3766	616.6351	45246.59	6.577495	6	10.	18.1
	32.02614	0.015	66.66667	43.184	-0.522	43.706	1712.875	74862.93	10.88282	9.5	16.7	11.6
	48.03922	0.01	100	28.797	-0.522	29.319	3853.97	112994.5	16.42601	17.3	25	6.3
	188.3891	0.00255	392.1569	7.238	-0.081	7.319	59269.04	433790.1	63.06006	113	98	1.67
choked	320.2614	0.0015	666.6667	4.376	-0.0419	4.4179	171287.5	756731.2	110.006	263	167	1.04
	Vmax,m/s	1/Re	Re	P (in)	P(out)	Delta P	ro*V**2	DP, Pa	DP, psi			
1/35 Trans	4.803922	0.1	10	535.185	-10.746	545.931	38.5397	21040.01	3.058586	1.64	2.3	125
1/51 Long	9.607843	0.05	20	267.59	-5.32	272.91	154.1588	42071.47	6.115929	3.36	4.6	62.5
	12.0098	0.04	25	214.08	-4.244	218.324	240.8731	52588.38	7.644771	4.25	5.75	50
	16.01307	0.03	33.33333	160.559	-3.16	163.719	428.2188	70107.56	10.19153	5.8	7.7	37.5
	19.21569	0.025	40	133.8	-2.61	136.41	616.6351	84115.2	12.22782	7.1	9.2	30.9
	32.02614	0.015	66.66667	80.28	-1.532	81.812	1712.875	140133.8	20.37124	12.5	15.3	17.9
	48.03922	0.01	100	53.52	-0.989	54.509	3853.97	210076	30.53875	20.2	23	12.5
	188.3891	0.00255	392.1569	13.42	-0.1787	13.5987	59269.04	805982	117.1656	128	90.2	3.1
choked	320.2614	0.0015	666.6667	8.091	-0.0808	8.1718	171287.5	1399728	203.4783			

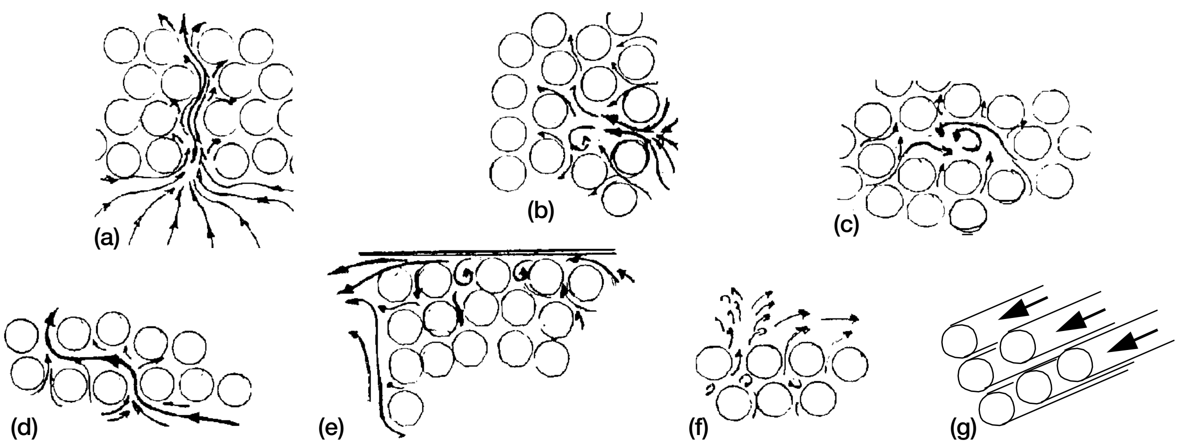

Figure 1.—Observed flow patterns in brush seals. (a) Rivering. (b) Jetting. (c) Vortical flow. (d) Lateral and parallel flow. (e) End-wall flow. (f) Flow at bristle tips. (g) Flow along bristles.

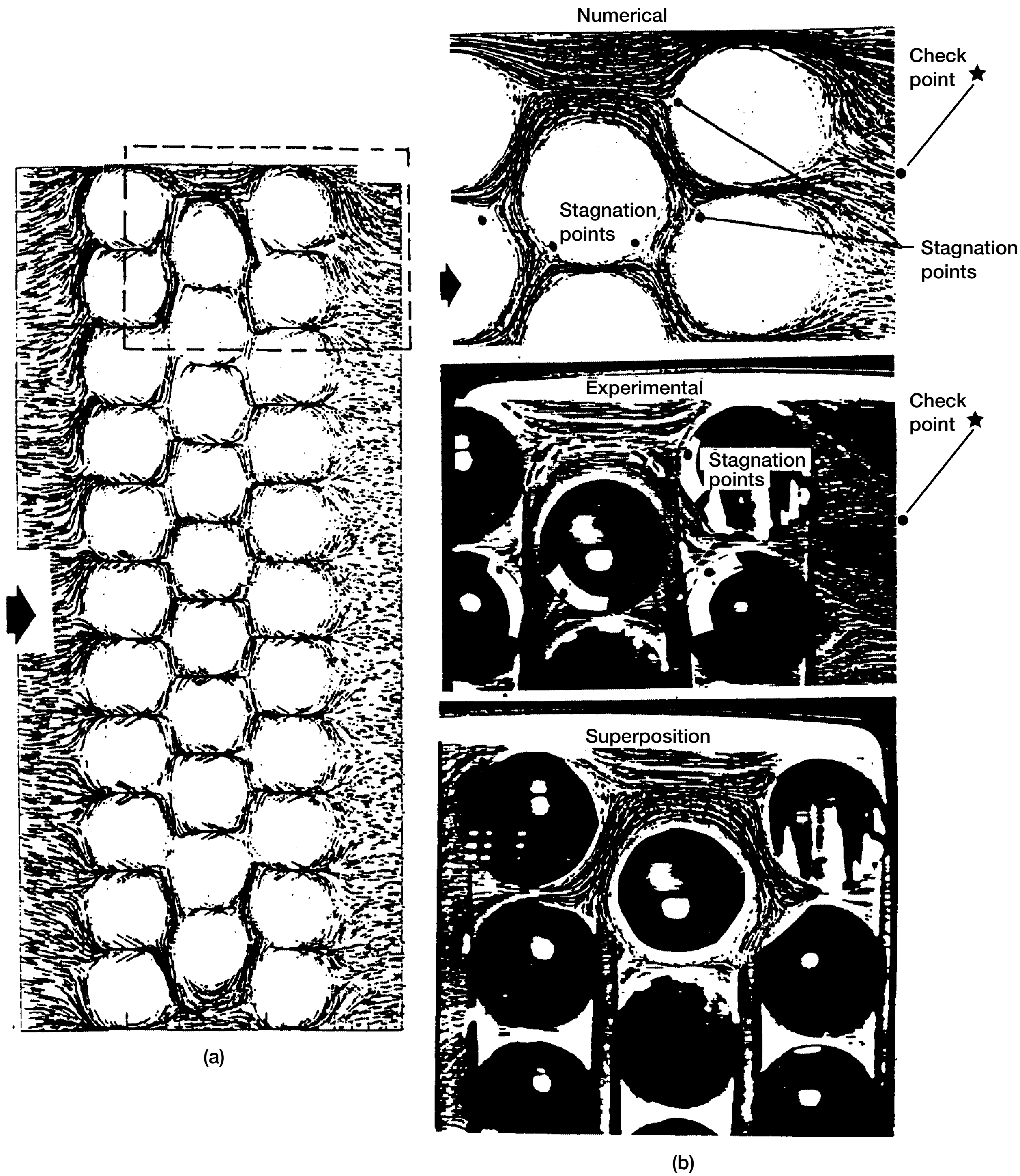

Figure 2.—Comparison of numerical and experimental results at Re = 195 for axial = transverse spaced array (a) array streamlines (b) flow details for section of (a): numerical, experimental, superposition (ref. 7).

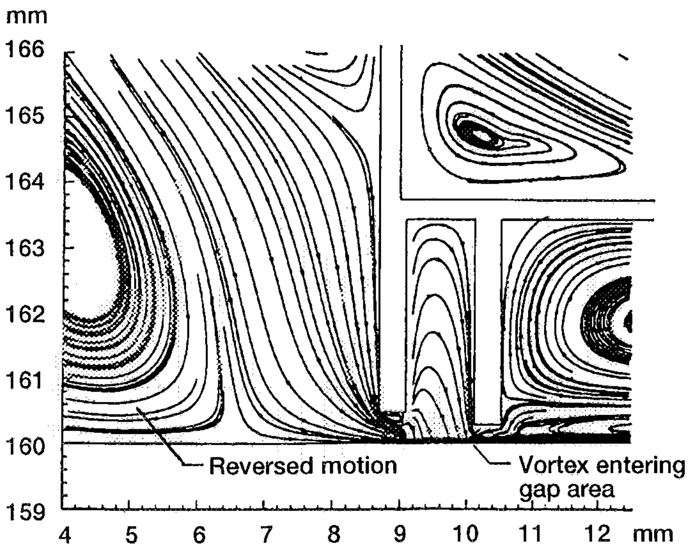

Figure 3.—Brush seal flow with inlet and exit flowfields with rotation, (Ref. 8).

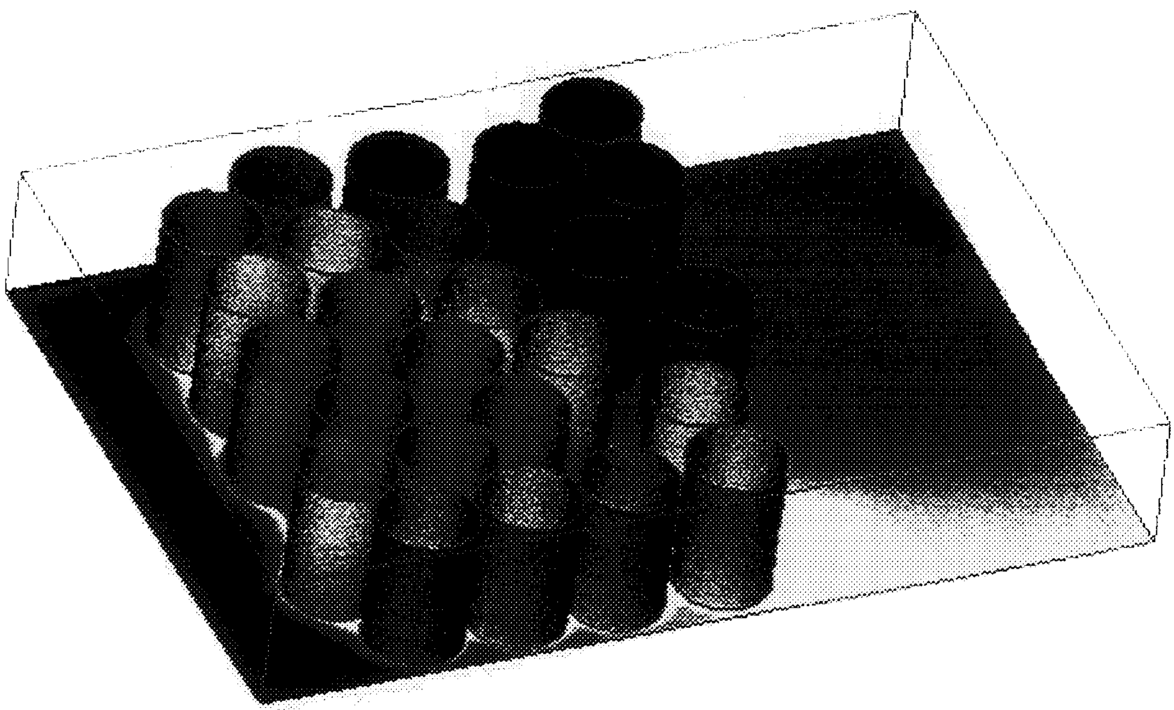

Figure 4.—Brush bristle surface temperature with tip heat transfer, (Ref. 9).

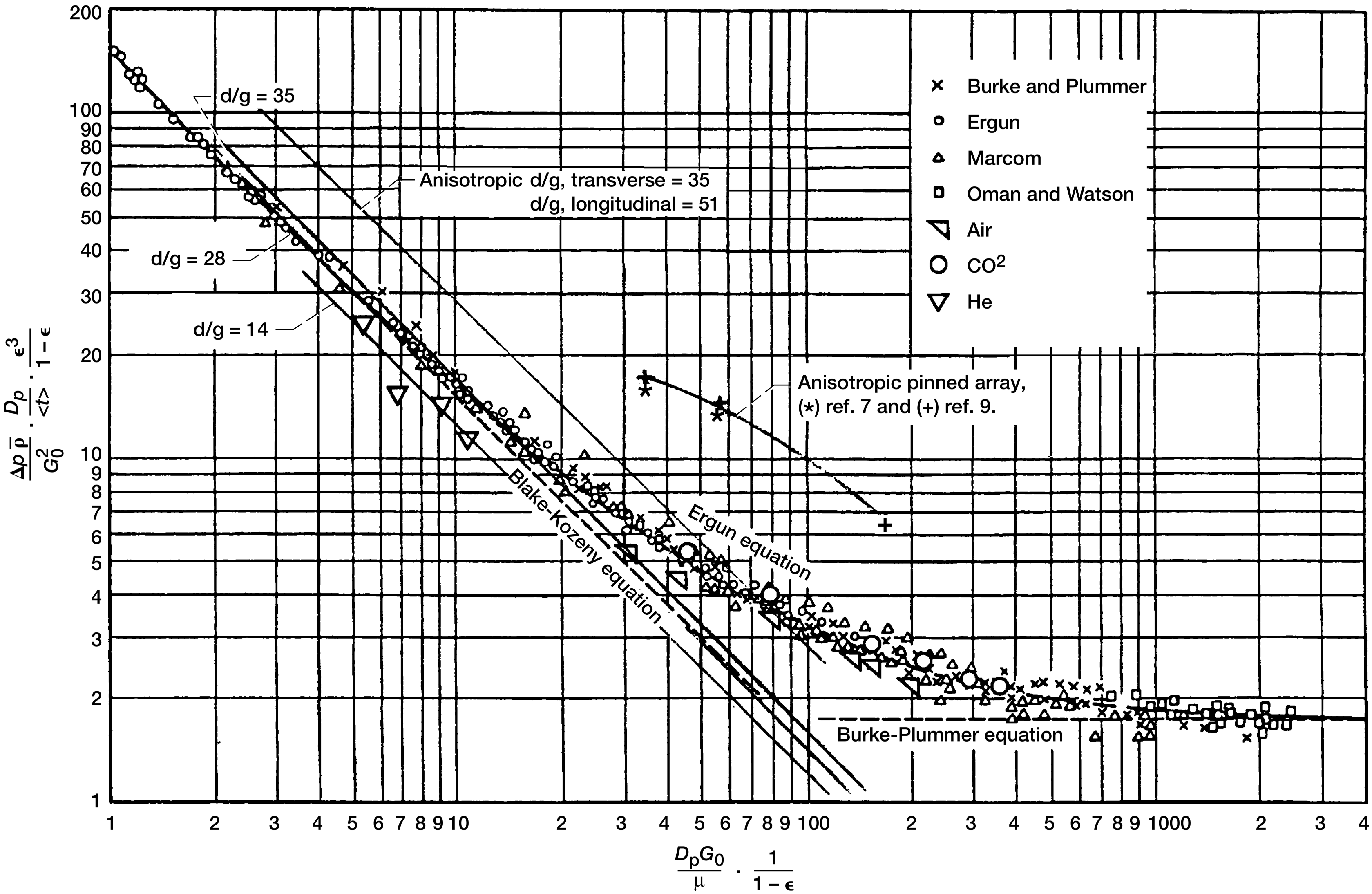

Figure 5.—Dimensionless flow loss versus Reynolds number taken from Ergun (10) with: (i) superimposed brush seal data for air, carbon dioxide, and helium from Carlile et al. (12). (ii) simple Ergun model and numerical model comparisons (iii) anisotropic array results from references 7 and 9; geometry is figure 10. Grid background from Bird, R. B., Stewart, W. E.; and Lightfoot, E. N: Transport Phenomena, John Wiley Press, New York, 1960, p. 200.

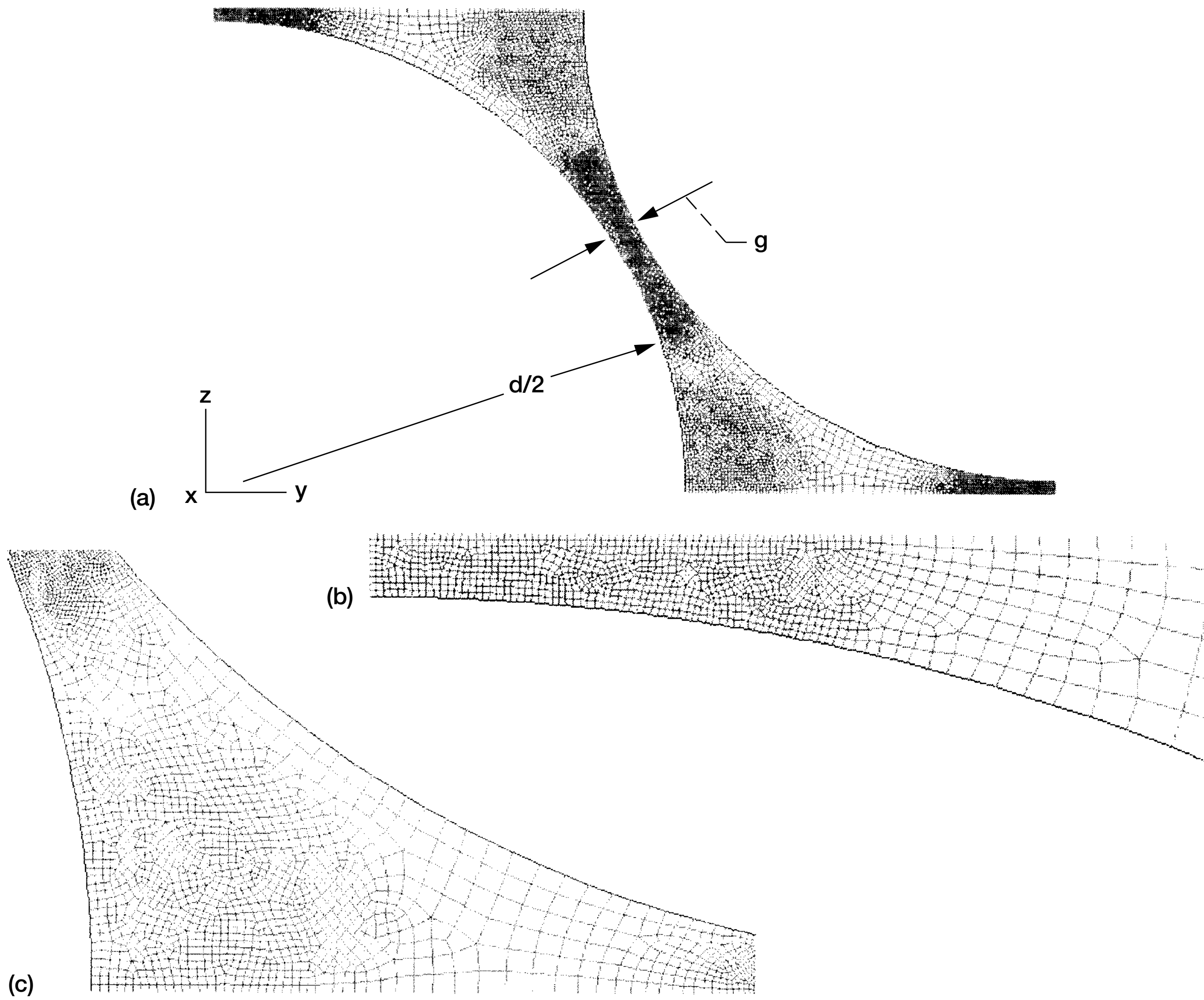

Figure 6.—Grid for FEM-model. (a) Overall. (b) Upper zone. (c) Lower zone.

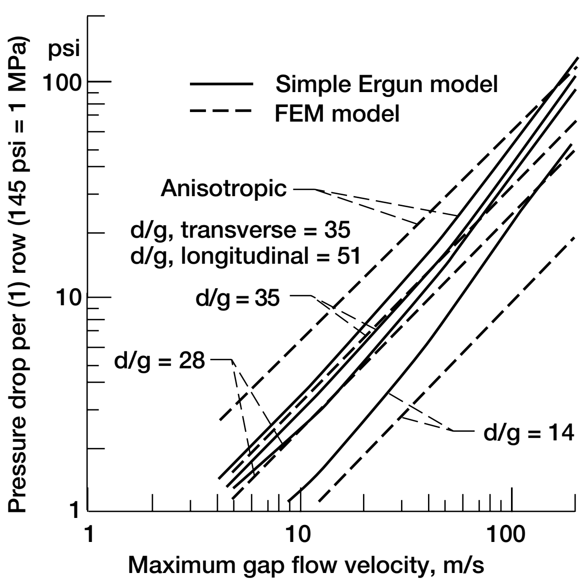

Figure 7.—Pressure drop verses maximum gap flow velocity at different packing densities.

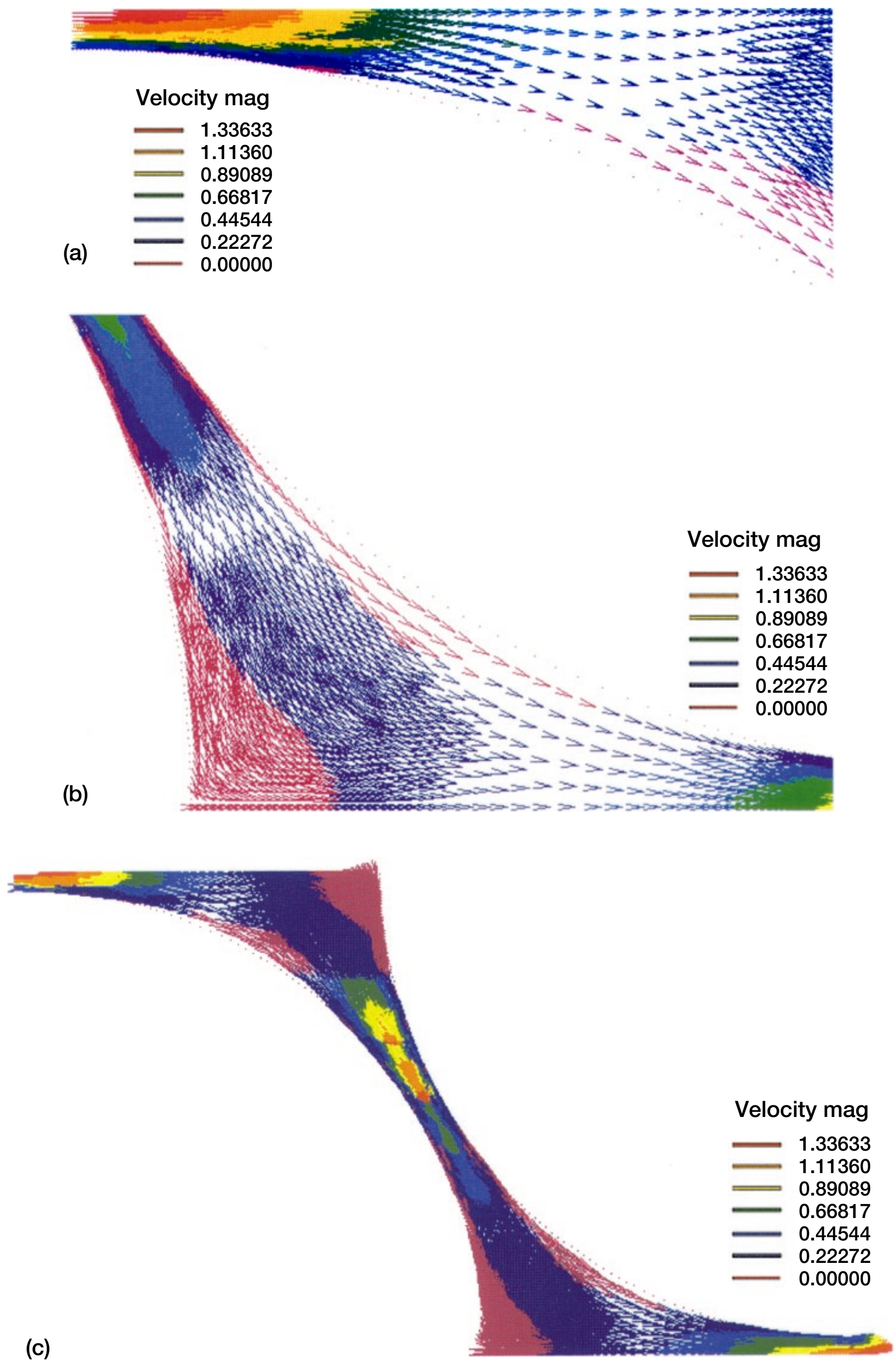

Figure 8.—Velocity field; simulated idealized brush seal with grid shown fig. 6, Re = 100; d/go = 35.

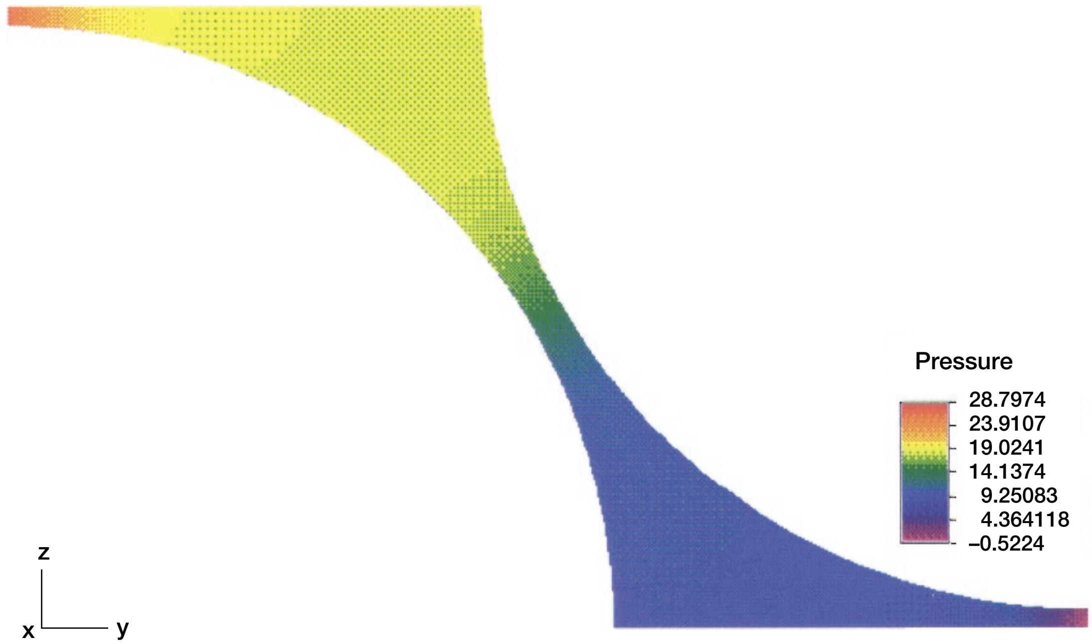

Figure 9.—Pressure field; simulated idealized brush seal with grid shown fig. 6, Re = 100; d/go = 35.

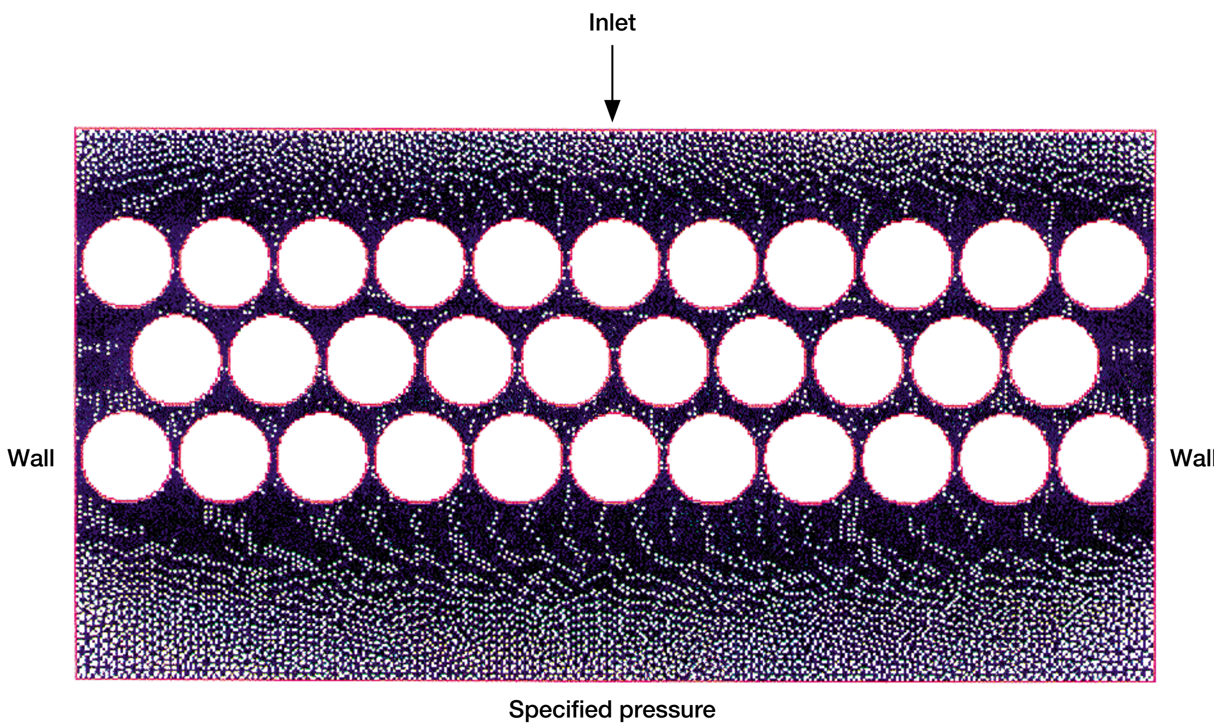

Figure 10.—Grid and boundary conditions for anisotropic pin array of reference 7, ref (9).

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13. ABSTRACT ***(Maximum 200 words)***

Flows through idealized pin arrays were investigated using an unstructured grid finite difference model and the simplified Ergun model to predict leakage flows and pressure drops in brush seals. The models are in good agreement in the laminar region with departures in the laminar-turbulent transition region defined by the simplified Ergun model. No local disturbancs in the velocity or pressure fields, sympotomatic of turbulence were found in the numerical results. The simplified model failed to predict the pressure drop of a 32–pin anisotropic array. Transitional and anisotropic behavior requires further investigation.

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