Warwick Turbulence Symposium
Joint Workshop and Graduate summer school:
Instabilities and Turbulence in MHD flows

EXPERIMENTAL OBSERVATIONS OF MHD TURBULENCE

with some emphasis on comparative aspects and analogies

Arkady Tsinober
Imperial College

Based mostly on

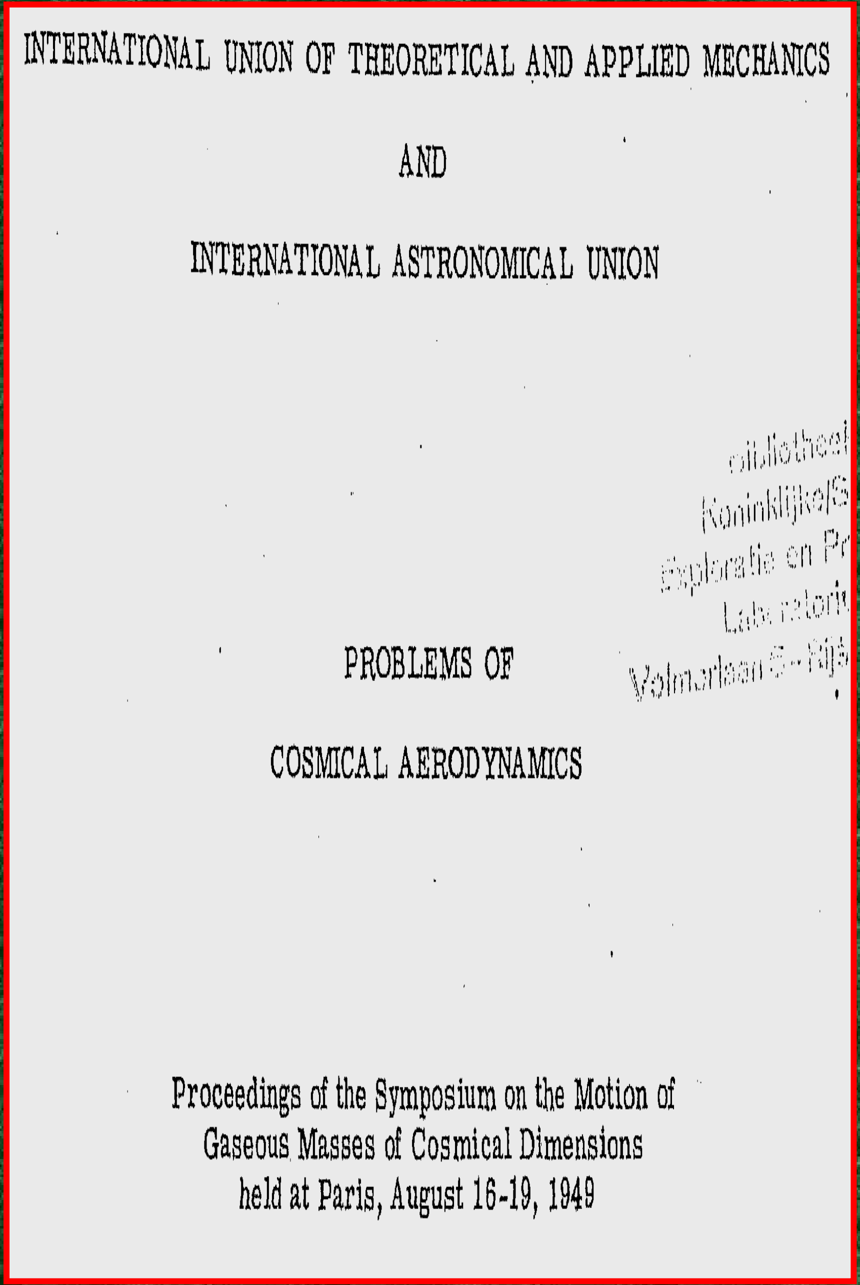
TSINOBER, A. (1975a) MHD turbulence, ***Magnitnaya Gidrodinamika***, 11, No.1,. 7 -22
TSINOBER, A. (1975b) The influence of the magnetic field on nonlinear hydrodynamic processes in liquid metals, pp. 314+104, *The Doctor dissertation* (*West equiv. Habilitation*),Riga, *In Russian, available on internet* 1469525355_tsinober-1973 150.pdf
TSINOBER, A. (1990) MHD flow drag reduction, in D.M. Bushnell and J.N. Hefner, Viscous drag reduction in boundary layers,, *Progr. Astronaut.Aeronaut.*, vol 123, ππ. 327–249.
MOREAU, R. THESS, A AND TSINOBER, A.. (2006) MHD Turbulence at Low Magnetic Reynolds Number: Current Status and Future Needs, in Magnetohydrodynamics: evolution of ideas and trends, Editors: S. Molokov, R. Moreau, H.K. Moffatt, Springer/Kluwer, in press.

It is extremely important to clarify the deviations from the ordinary laws of hydrodynamics caused by magnetic fields.

W. HEISENBERG, in *Problems of Cosmical Aerodynamics, Proceedings of Symposium* "Problems of motion of gaseous masses of cosmical dimensions", Paris, August 1949.

A clearer understanding of turbulent hydromagetic flows will result in greater insight into stricty hydrodynamic turbulence and into the mechanism of transition between laminar and turbulent flow regimes

L.P. HARRIS, Hydromagnetic channel flows, Wiley, 1960, p.2



INTERNATIONAL UNION OF THEORETICAL AND APPLIED MECHANICS

AND

INTERNATIONAL ASTRONOMICAL UNION

PROBLEMS OF

COSMICAL AERODYNAMICS

Proceedings of the Symposium on the Motion of
Gaseous Masses of Cosmical Dimensions
held at Paris, August 16-19, 1949

The following scientists took part in the meetings:

Belgium:	R. Coutrez (Uccle, Bruxelles); R. Drumaux (Gent); P. Ledoux (Liege).
Denmark:	B. Strömgren (Copenhagen); M. Rudkjöbing (Copenhagen).
Finland:	J. Tuominen (Helsinki, temporarily at Delft (Holland)).
France:	D. Barbier (Paris); A. Danjon (Paris); J. Delhaye (Paris); P. Guintini (Paris); J. Kampé de Fériet (Lille); M. Laffineur (Paris); H. Mineur (Paris); J. C. Pecker and Mad. Ch. Pecker (Paris); J. Pérès (Paris); E. Schatzman (Paris); G. de Vaucouleurs (Paris).
Germany:	W. Heisenberg (Göttingen); C. F. von Weizsacker (Gottingen).
Great Britain:	G. K. Batchelor (Cambridge); Mrs. E. M. Burbidge (London); F. Hoyle (Cambridge); R. A. Lyttleton (Cambridge); G. C. McVittie (London); G. Temple (London).
Italy:	Miss L. Zappa (Merate, Como).
Netherlands:	J. M. Burgers (Delft); H. C. van de Hulst (Leiden); C. de Jager (Utrecht); Miss H. A. Kluyver (Leiden); M. Minnaert (Utrecht); J. H. Oort (Leiden).
Sweden:	H. Alfvén (Stockholm); B. Lindblad (Stockholm); C. Walén (Stockholm).
Switzerland:	F. Egger (Zurich).
United States of America:	G. Colchagoff (Dayton, Ohio); L. DuBridge (Pasadena, California); Mrs. C. Payne-Gaposchkin (Cambridge, Mass.); P. van de Kamp (Swarthmore, Pa.); Th. von Karman (Pasadena, California); H. Liepmann (Pasadena, California); S. C. Lowell (Off. Nav. Res., temporarily in London); F. E. Marble (Pasadena, California); N. U. Mayall (Lick Obs., California); J. von Neumann (Princeton, N. J.); S. A. Schaaf (Berkeley, California); R. J. Seeger (Silver Spring, Md.); H. Shapley (Cambridge, Mass.); L. Spitzer (Princeton, N. J.); F. Zwicky (Pasadena, California).

Compared with some other branches of fluid mechanics, there is relatively litle basic research in turbulence at the moment, yet it may be more than any time in the past. Probably not more than fifty people in the world are active in the field. This is in sharp contrast, for example, to the fascinating, fashionable and important new area of "magnetohydrodynamics" or plasma dynamics", probably pursued by thousands. S. CORRSIN (1961) Turbulent flow, *American scientist*, **49,** p. 322.

SOME EMPHASIS ON

Comparative aspects

Anistropy, quasi-two-dimensional states and asymptotic behavior

MHD as a means of studying general issues of fluid dynamics

And references originating from former Soviet Union

CHANNEL FLOW ⊥ FIELD

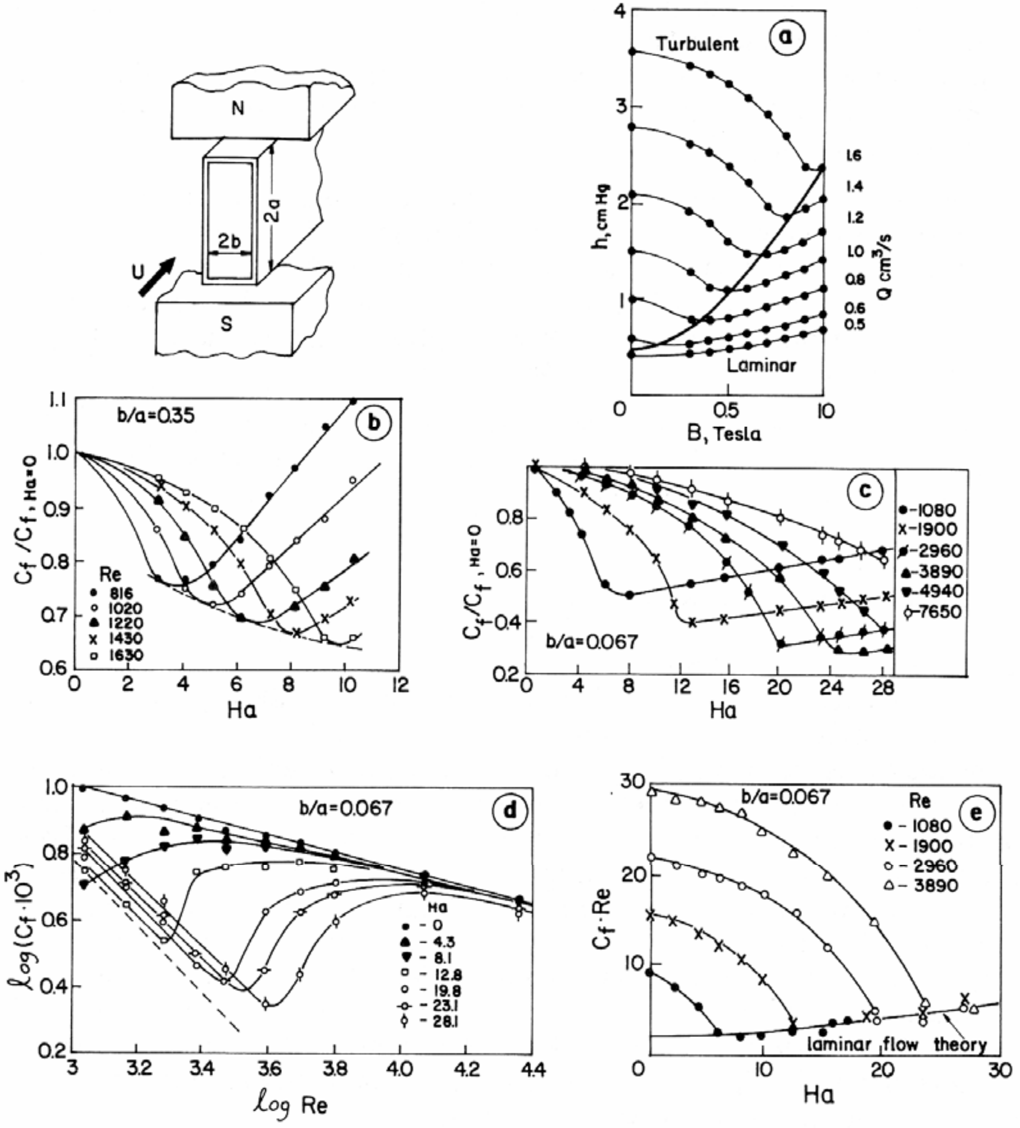


Fig. 3 Drag-reduction effect of an azimuthal magnetic field on liquid methal flow: a) example of the results obtained by Hartmann and Lazarus[10]; b) same as part a in nondimensional form; c–e) results for $b/a = 0.067$ in different representations (see Refs. 11 and 12). (The full line in part e corresponds to the exact solution by Shercliff for laminar flow[13]).

HARTMANN & LAZARUS 1937

Repeated and extended, see refs in TSINOBER 1990

PIPE FLOW ||FIELD

KOVNER & KRASIL'NIKOV 1966

Repeated and extended, see refs in TSINOBER 1990

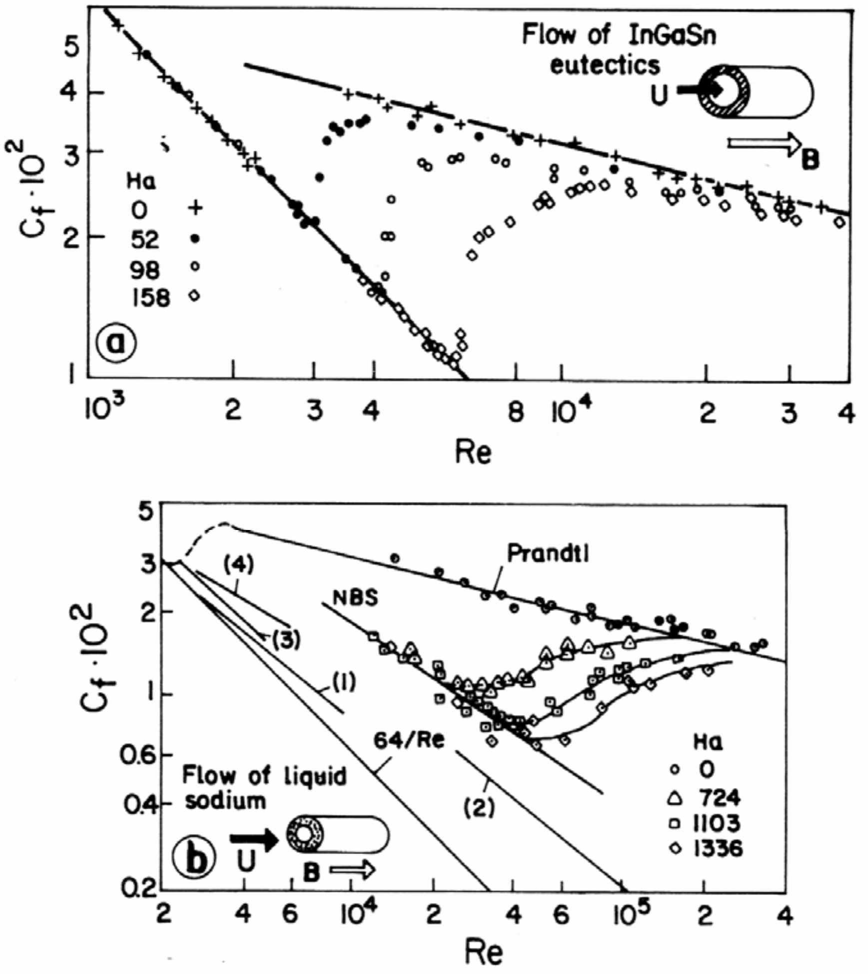
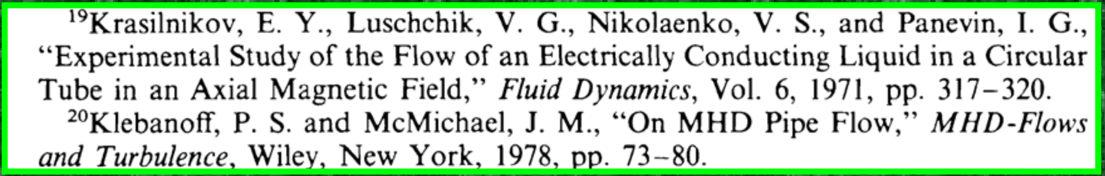


Fig. 6 Drag reduction in a circular pipe by a longitudinal magnetic field: a) results from Ref. 19; b) results from Ref. 20 with comparison with other sources [(1),[21] (2),[22] (3),[23] (4)[24]].



[19] Krasilnikov, E. Y., Luschchik, V. G., Nikolaenko, V. S., and Panevin, I. G., "Experimental Study of the Flow of an Electrically Conducting Liquid in a Circular Tube in an Axial Magnetic Field," *Fluid Dynamics*, Vol. 6, 1971, pp. 317–320.

[20] Klebanoff, P. S. and McMichael, J. M., "On MHD Pipe Flow," *MHD-Flows and Turbulence*, Wiley, New York, 1978, pp. 73–80.

SUPPRESSING

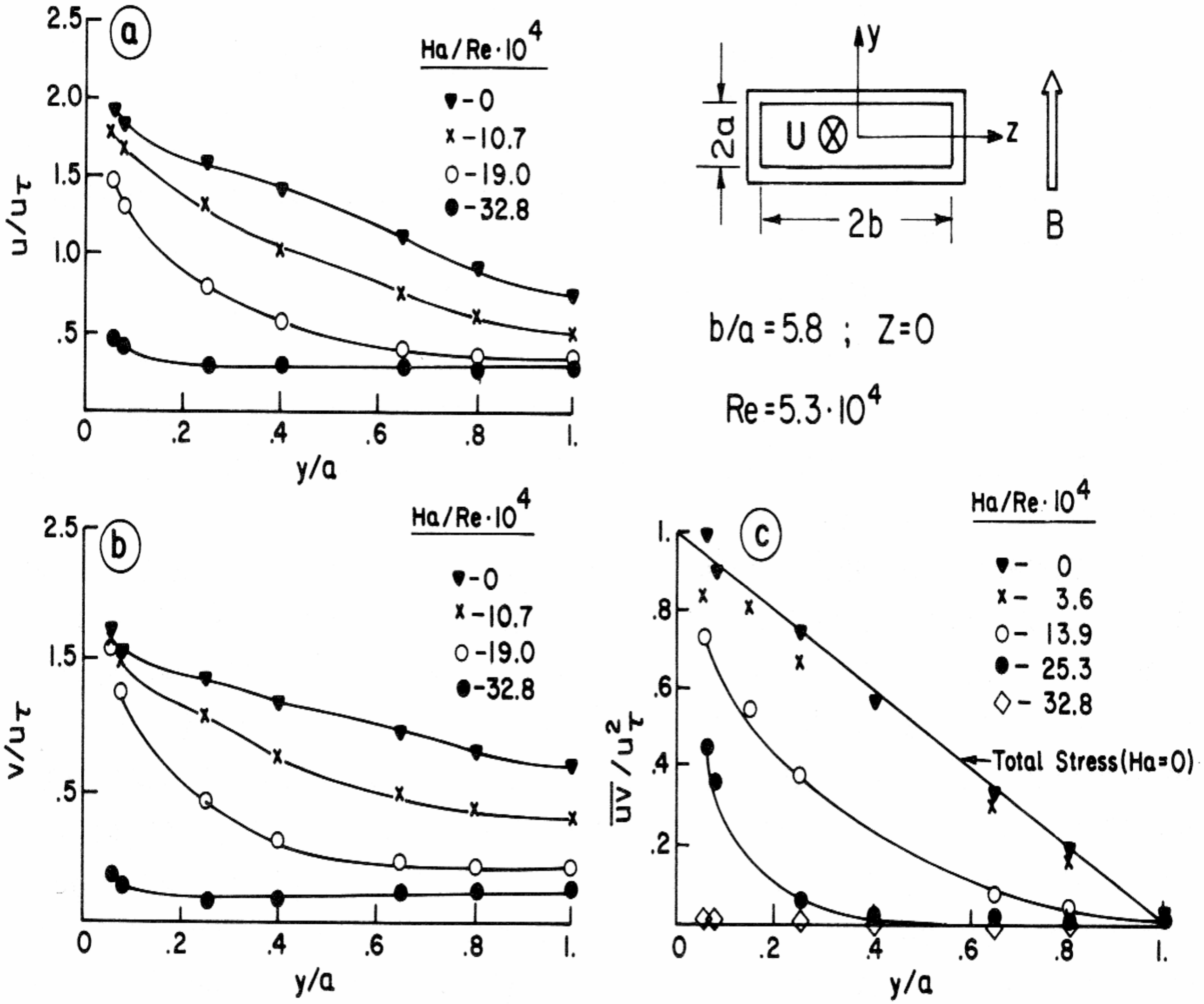


Fig. 12 The effect of a magnetic field on turbulence structure in a rectangular channel.[35] Root mean square value of: a) longitudinal velocity fluctuations, b) transverse velocity fluctuations, and c) turbulent shear stress.

SUPPRESSING?

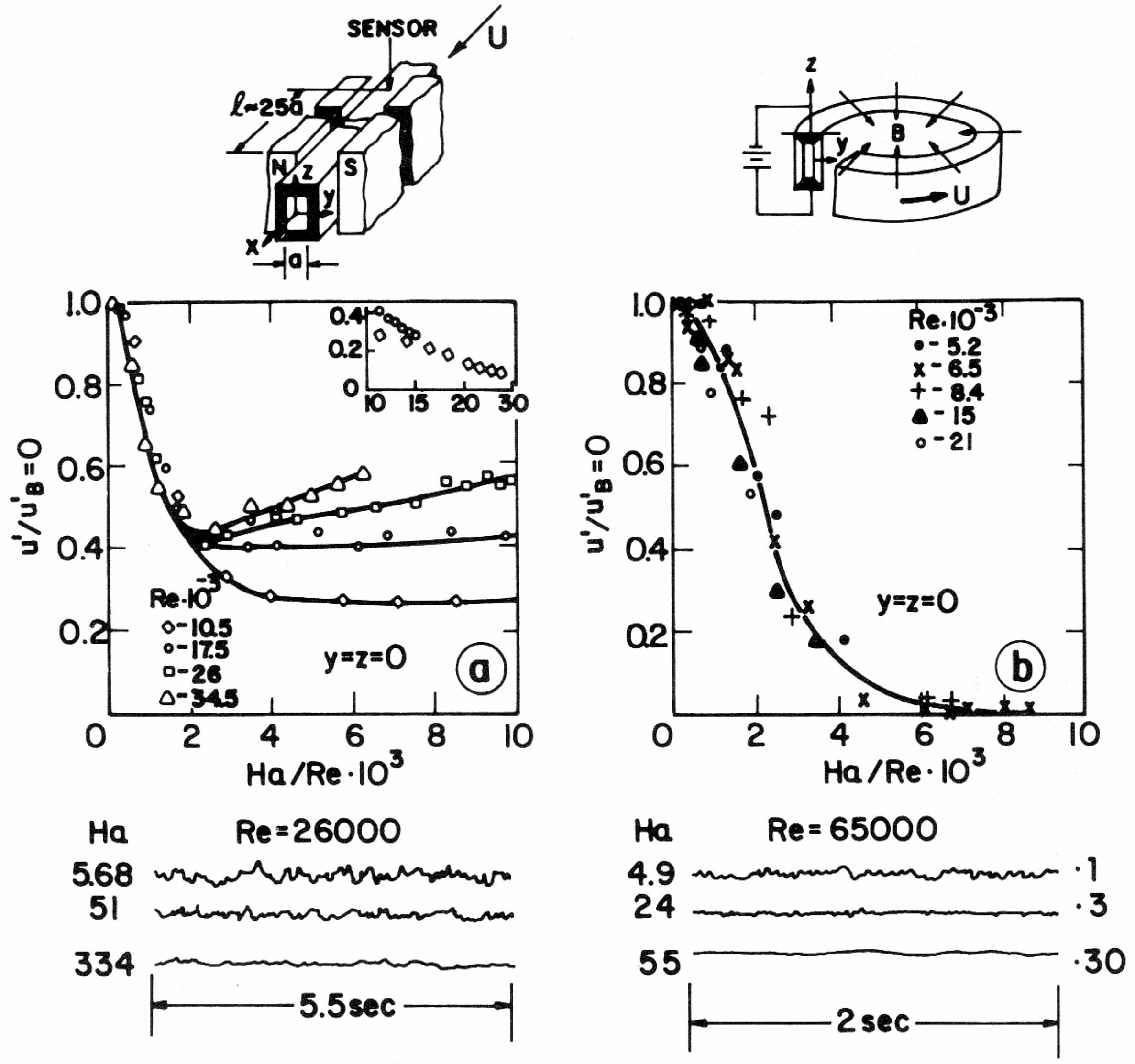
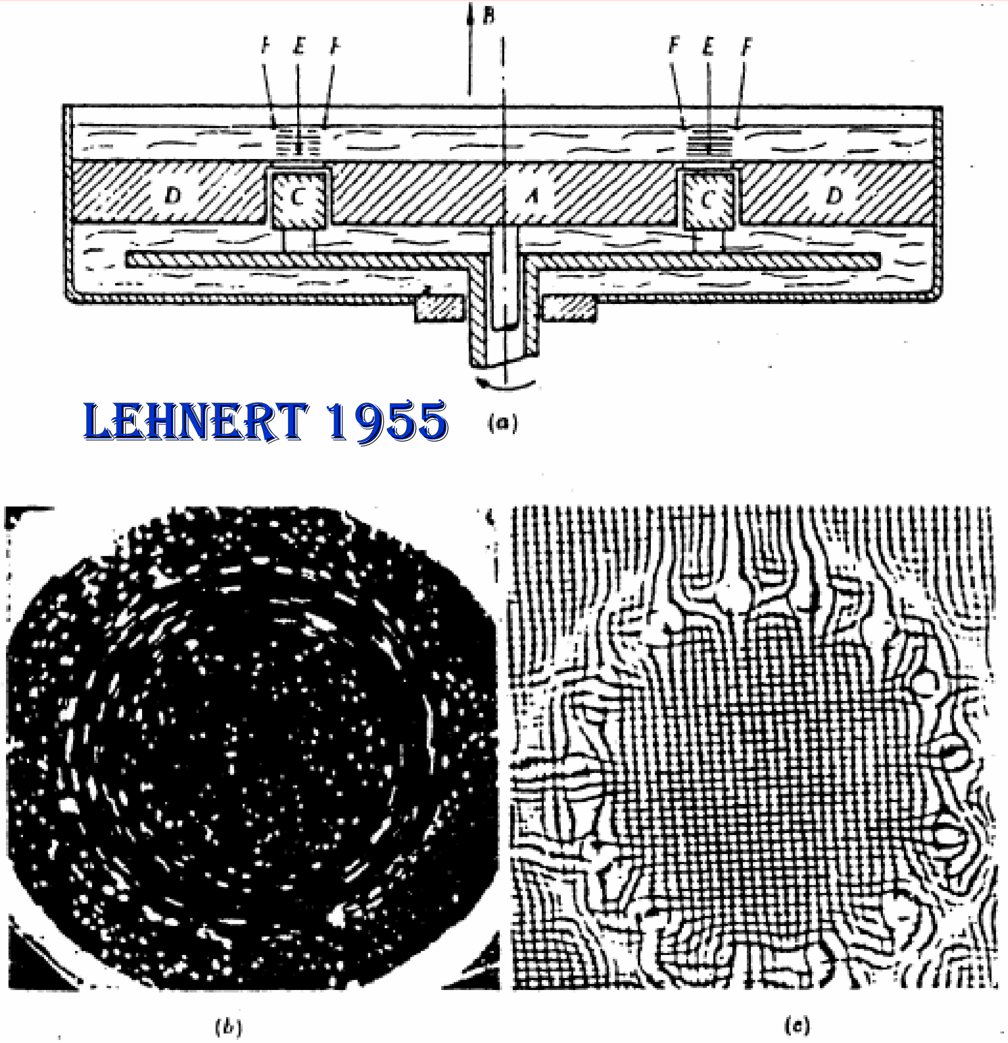


Fig. 9 Intensity (rms) of the longitudinal velocity component of turbulent fluctuations[28]: a) straight channel with finite length of the imposed magnetic field; b) annular "infinitely long" channel.

PRODUCING?



(a)

(b) (c)

(a) Apparatus for studying the motion of mercury above rotating copper disks in the presence of an external magnetic field. (b) The mercury surface seen from above when $B = 4300$ gauss. The mean motion has been indicated with grains of sand. (c) The reflection of a wire grid shows the deformation of the surface during the motion. A number of stationary whirls are produced on both sides of the moving ring of mercury. (After Lehnert, 1955b.)

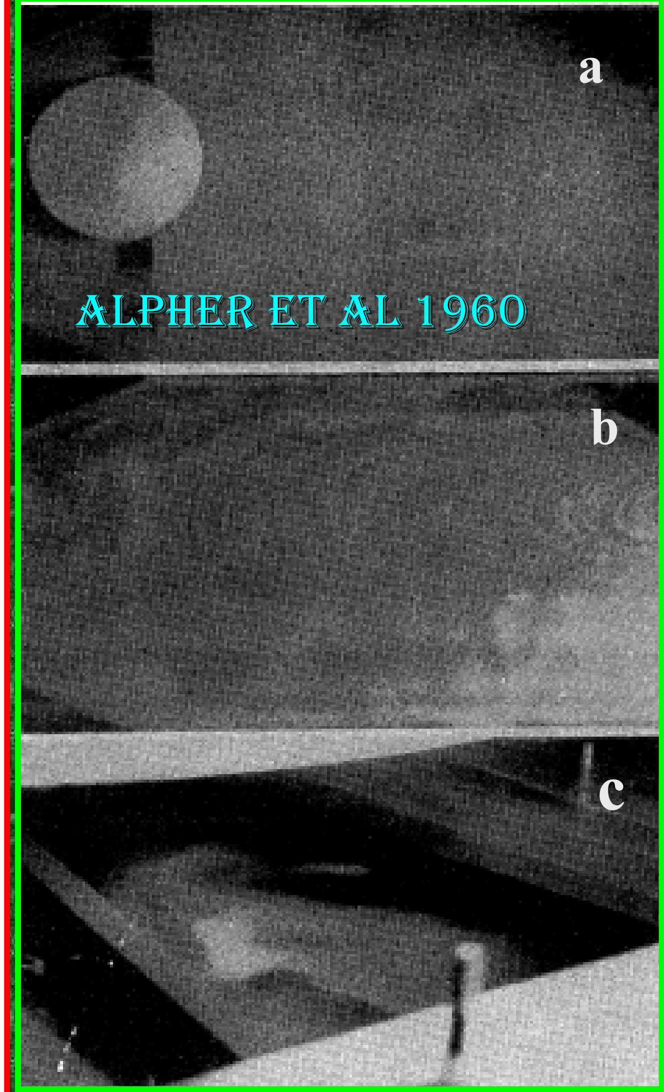
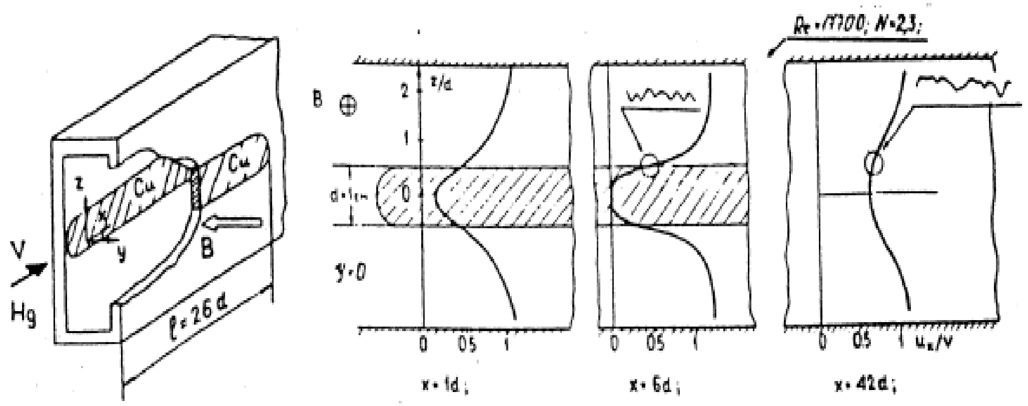
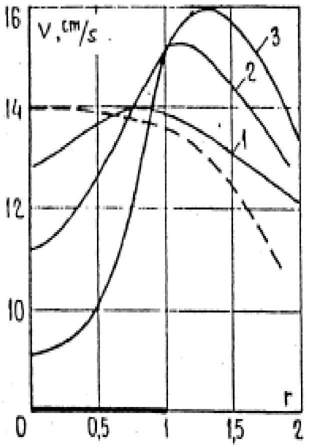


FIG. 7. In (a) is seen a 2-cm radius copper disk, 0.013 cm thick, on the channel bottom—the view being as in Fig. 6. In (b) surface dirt shows the magnetohydrodynamic effect of a low-velocity flow over the disk at 4200 gauss. In (c) one has a view of the channel flow over the disk while looking upstream. The velocity is such that the disk is shedding a vortex street.

WALLS WITH INHOMGENEOUS CONDUCTIVITY





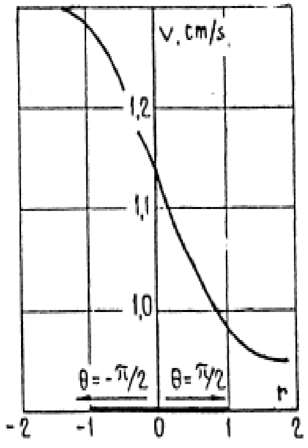


Fig. 6. Distribution of velocities in the direction of the flow at a distance $y=0.8$ from the insert. $B=0.92$ T.

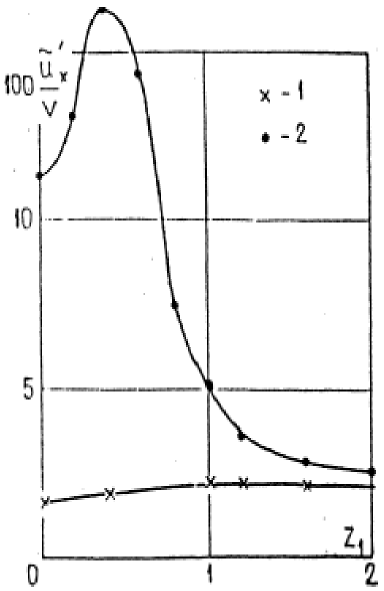
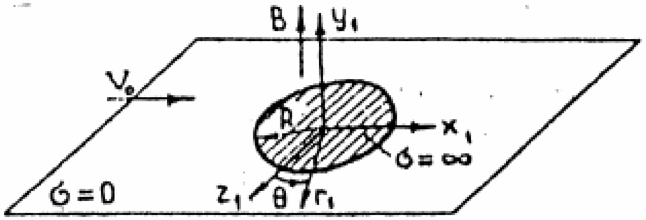
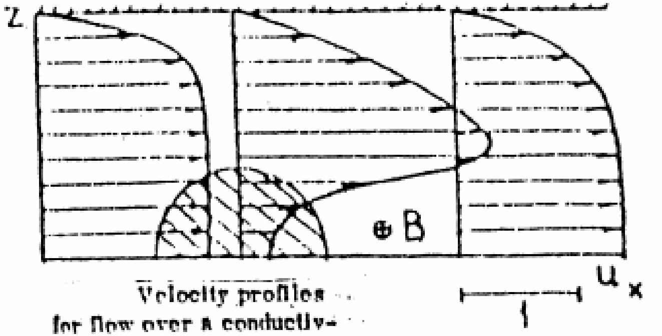


Fig. 5. Profiles of the velocities, measured in the plane $y=0.8$ with $B=0.92$ T: 1) at the leading boundary of the insert; 2) in the middle part of the insert; 3) at rear boundary of insert. The dashed curve denotes the velocity profile without insert.

Fig. 7. Profiles of the intensity of the pulsations of the longitudinal velocity: 1) in the plane $r_1=R$ $(\theta=-\pi/2)$; in the plane $r_1=4R$ $(\theta=\pi/2)$. $B=0.92$ T.



DNS

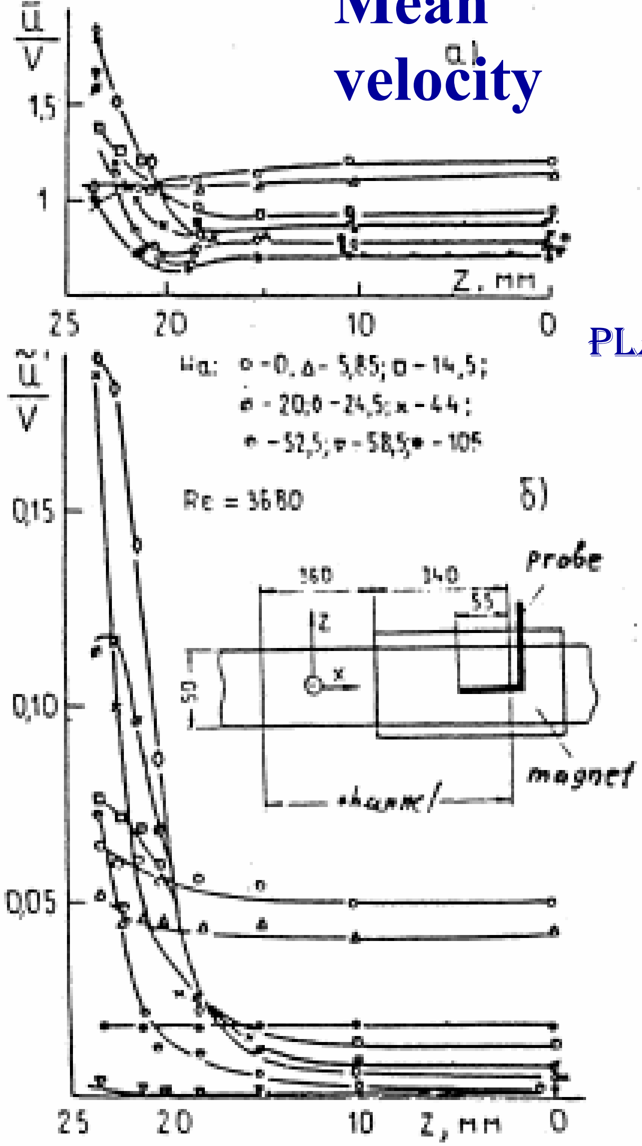


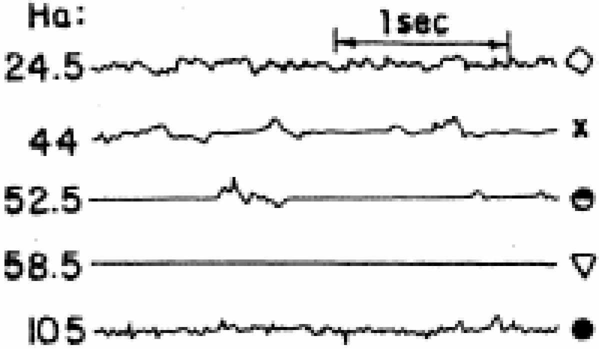
Velocity profiles for flow over a conductivity inhomogeneity on a duct wall; cross section $x_1=0.05$.

$Re=20;\ N=10$

ELECTRICALLY CONDUCTIVE HARTMANN WALLS

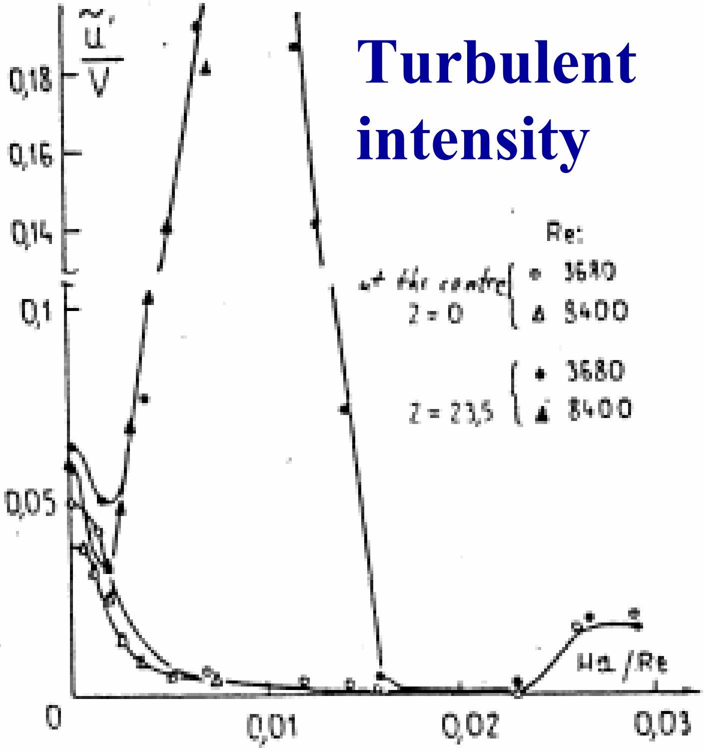
Mean velocity





PLATNIEKS & FREIBERGS 1972

Turbulent intensity



SUPPRESSING OR ENHANCING ?

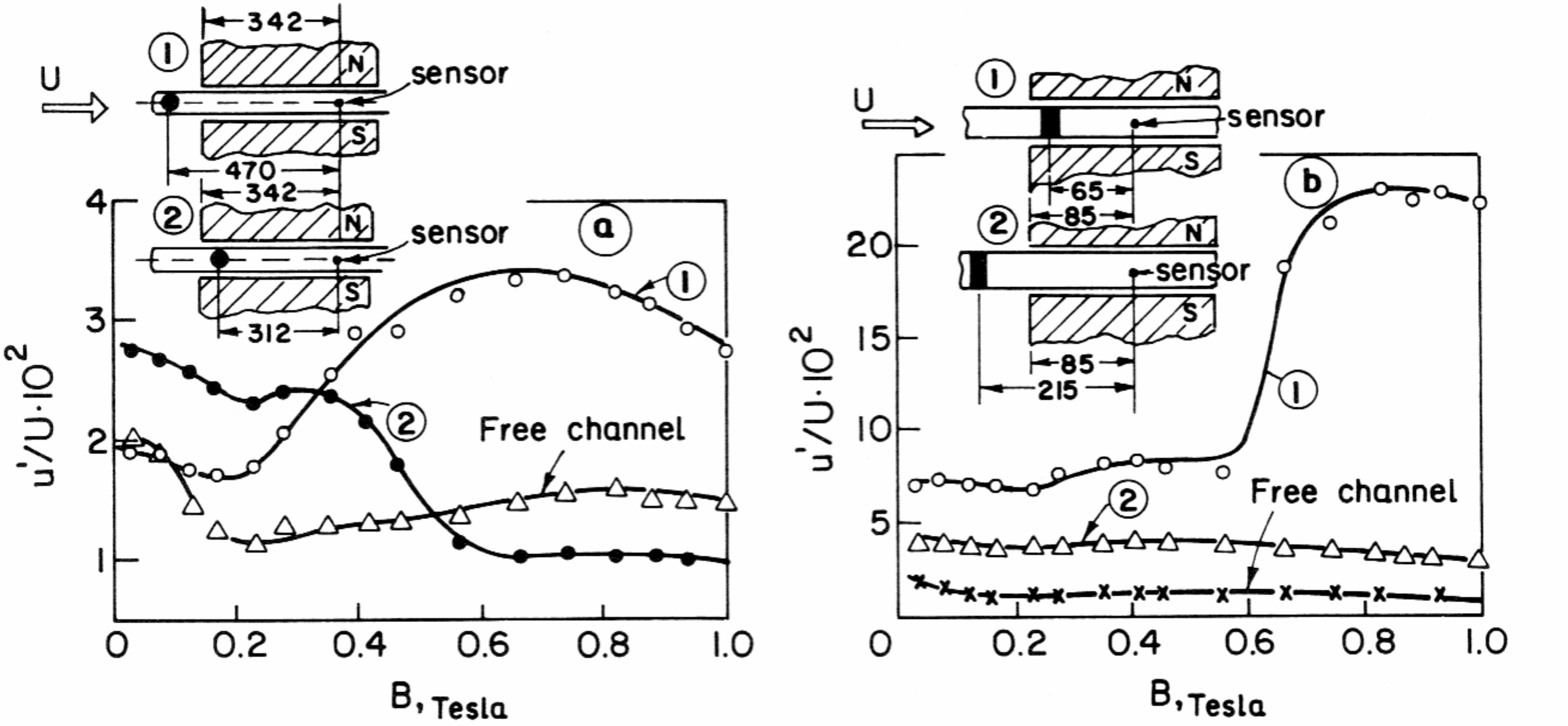


Fig. 10 The effect of a magnetic field on the perturbations on the wake behind a cylinder[29]: a) cylinder axis perpendicular to the magnetic field; b) cylinder axis parallel to the magnetic field.

[29] Kit, E., Turuntaev, S. V., and Tsinober, A., "Investigation with Conduction Anemometer of the Effect of Magnetic Field on Disturbances in the Wake of a Cylinder," *Magnetohydrodynamics*, Vol. 5, 1970, pp. 331–335.

Q2D STRUCTURE

KIT, L. & TSINOBER, A. 1971

On the possibility of realization and investigation of 2-D turbulence in strong magnetic field, *Magnetohydrodinamics*, 7(3), 27-34.

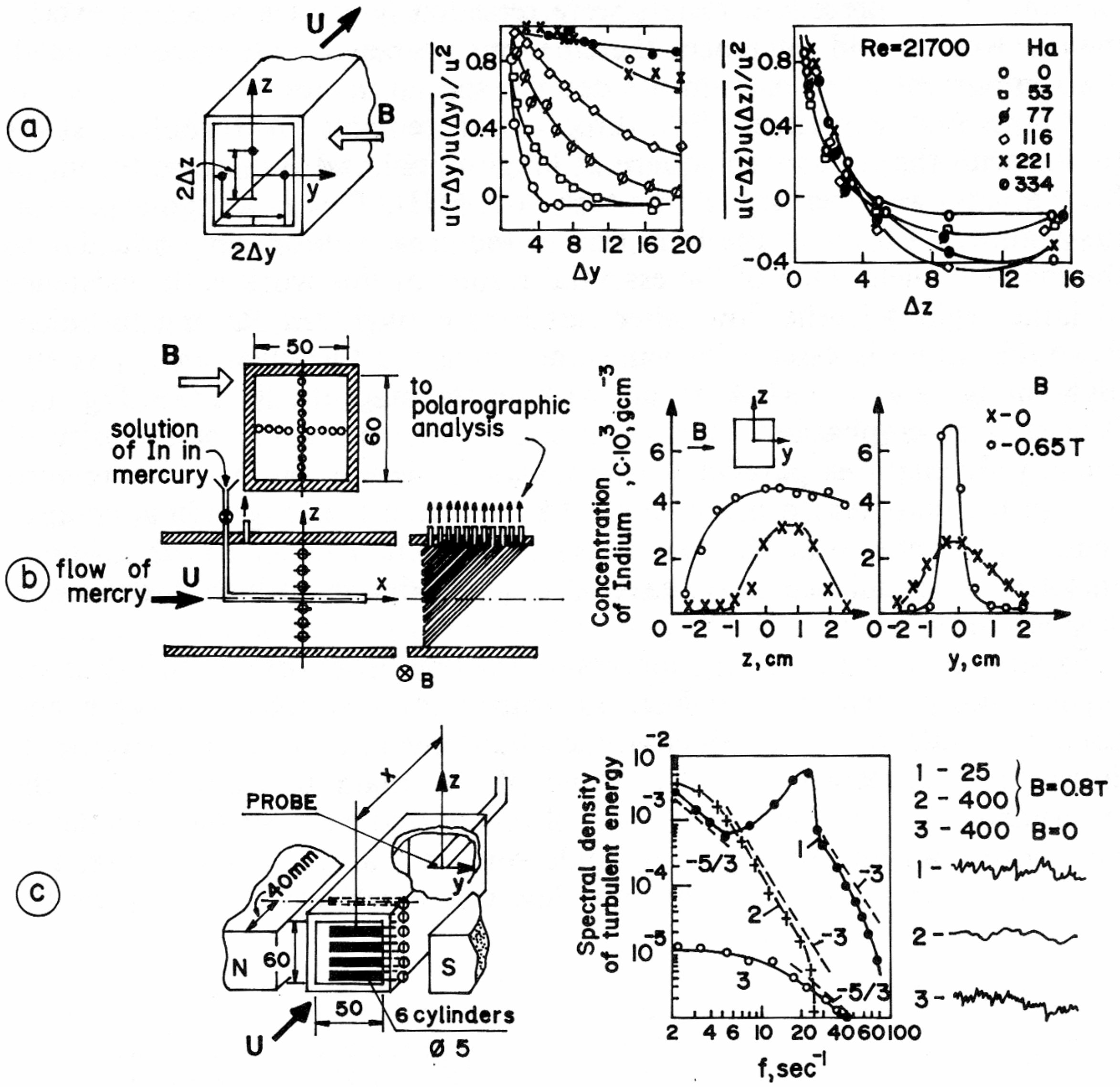
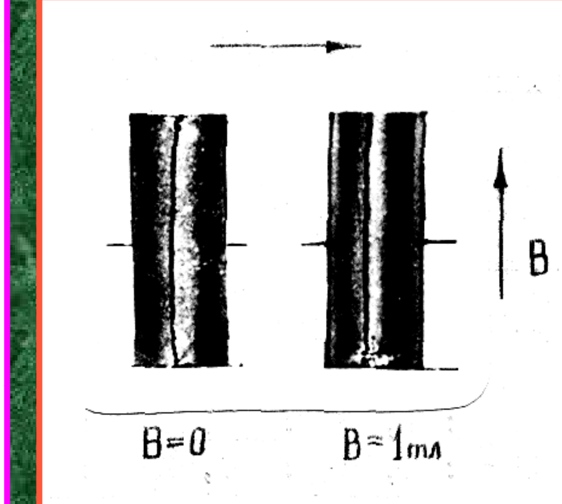
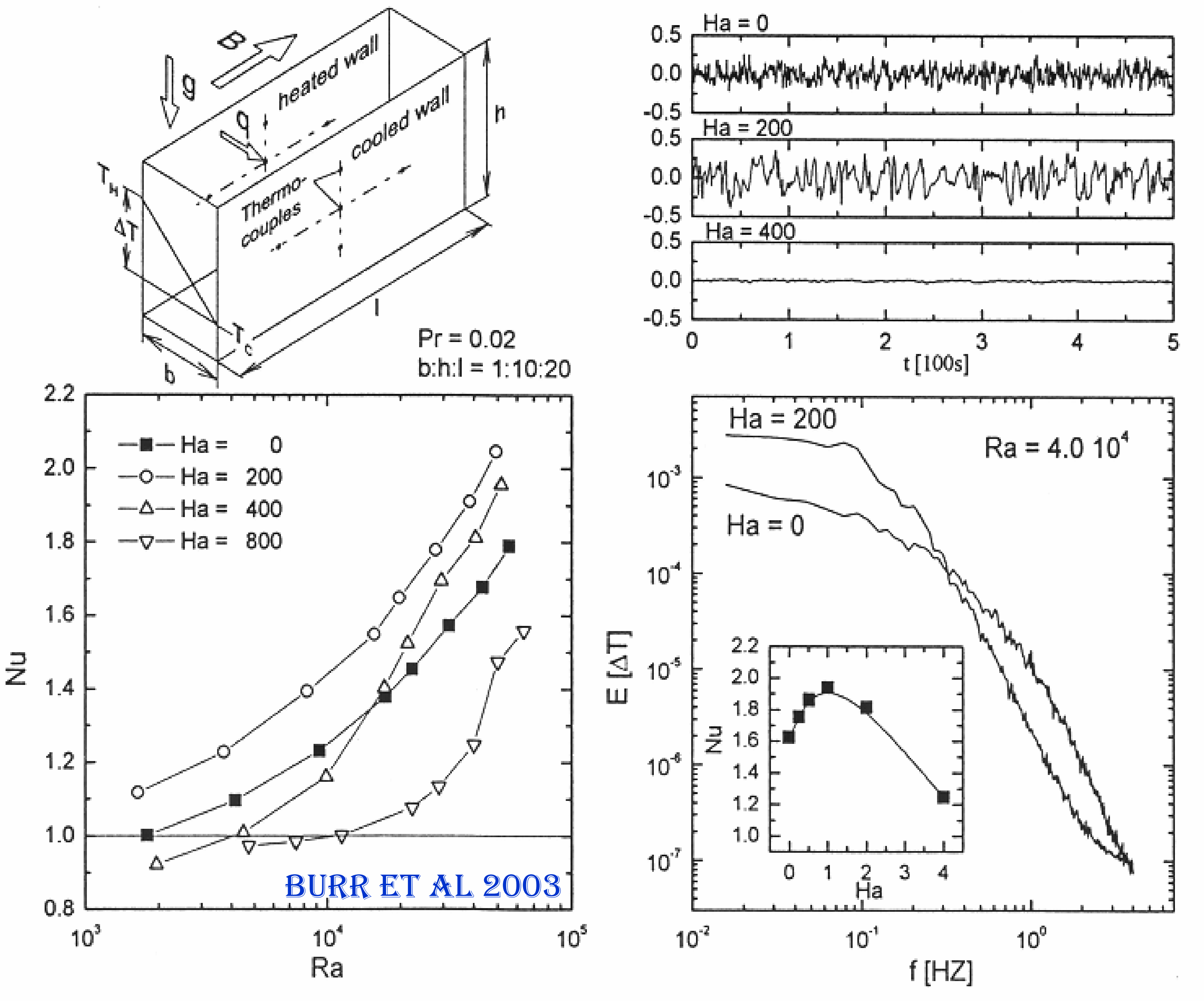


Fig. 11 Experimental results confirming the two-dimensional structure of turbulence in a strong magnetic field: a) spatial correlations,[31] b) mass transfer, and c) fluctuations spectra in the flow past a two-dimensional grid.[32]



CONVECTION IN A VERTICAL SLOT



BURR ET AL 2003

ELECTRICALLY DRIVEN

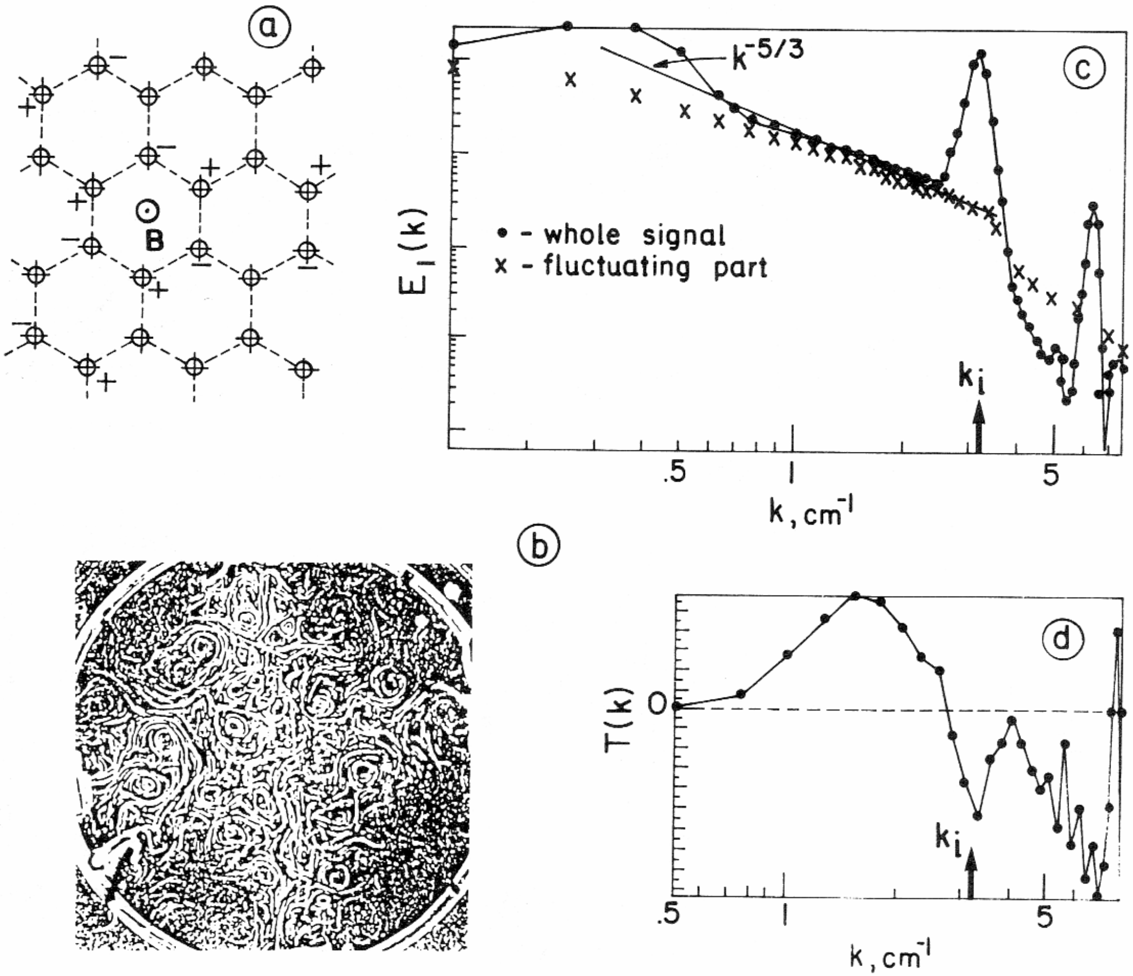


Fig. 13 Two-dimensional turbulence in electrically driven two-dimensional flows[40]: a) a fragment of a box with hexagonal system of a total of 282 electrodes; b) streaks of turbulence with inverse energy cascade; c) one-dimensional spatial spectrum of the longitudinal velocity component (the peaks correspond to the forcing wave number k_i and its harmonic); d) one-dimensional Fourier transform of a triple velocity correlation $\langle u_1(x)u_1(x)u_1(x+r)\rangle$, indicating a reverse energy cascade at small k (positive $T(k)$).

Always Q2D structure?

Grid flow ⊥ field

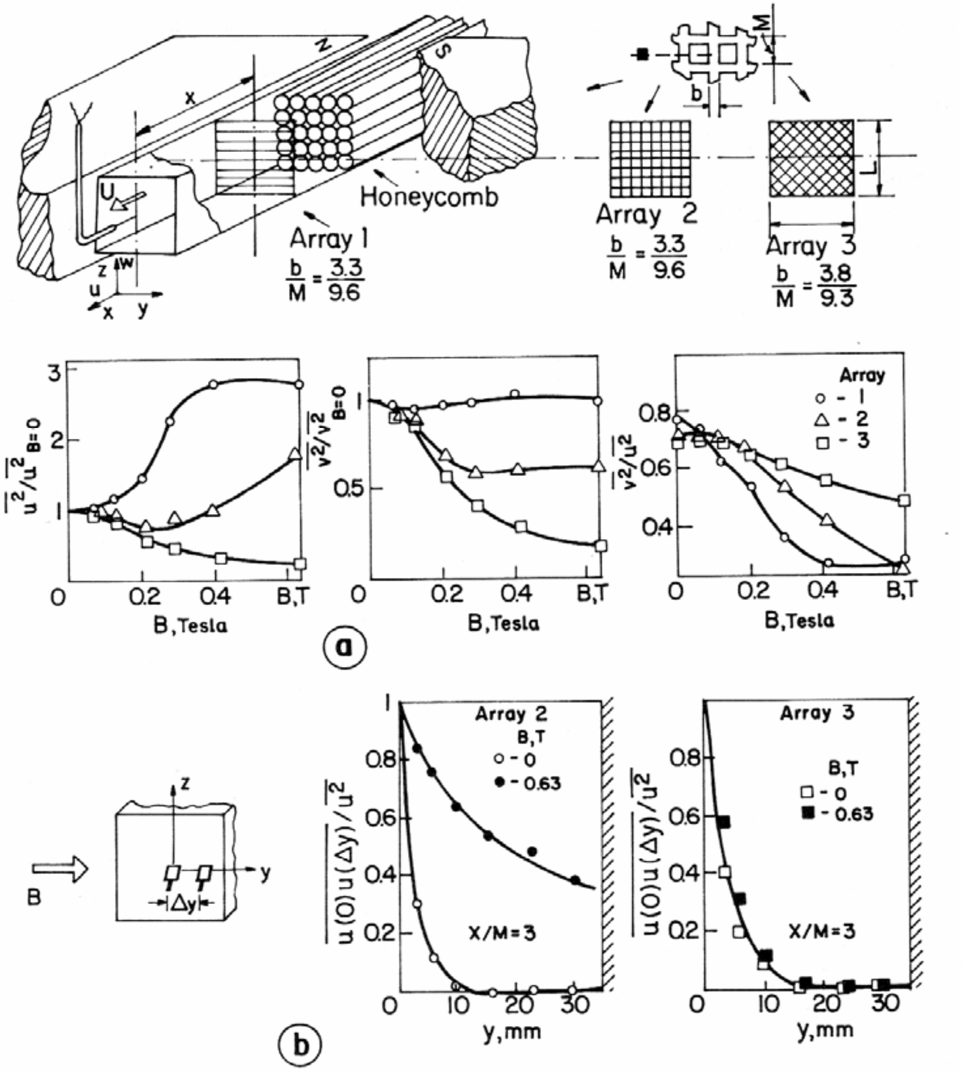
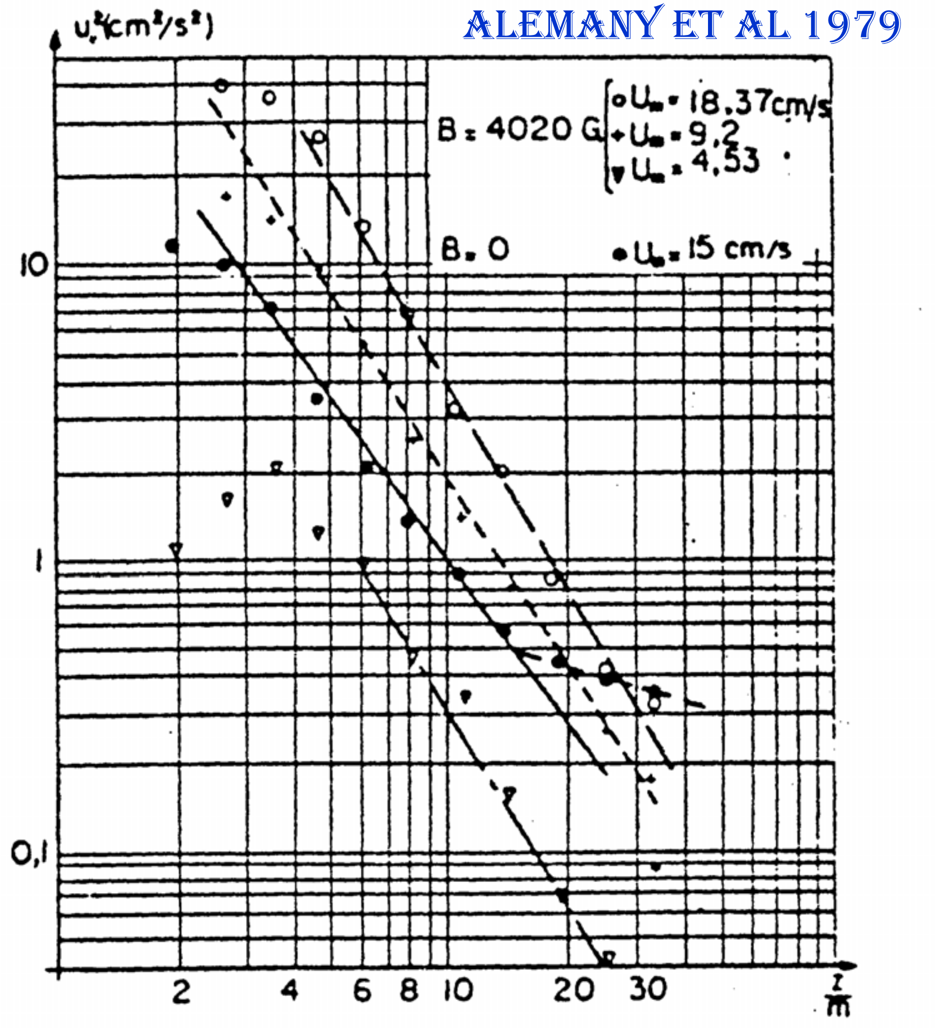


Fig. 14 Turbulence past grids of different geometry in a transverse magnetic field[44]: a) turbulence intensities, b) spatial correlation coefficients. It is seen that only the grid in the form of a grating, with cylinders parallel to the magnetic field as in Refs. 32 and 33 (i.e., favoring two-dimensional disturbances with their axis parallel to the magnetic field), produces turbulence of much higher intensity than without a magnetic field.

GRID FLOW || FIELD

ALEMANY ET AL 1979



– Evolution de l'intensité de turbulence derrière la grille sans origine fictive.

– *Evolution of the turbulence intensity behind the grid without effective origin.*

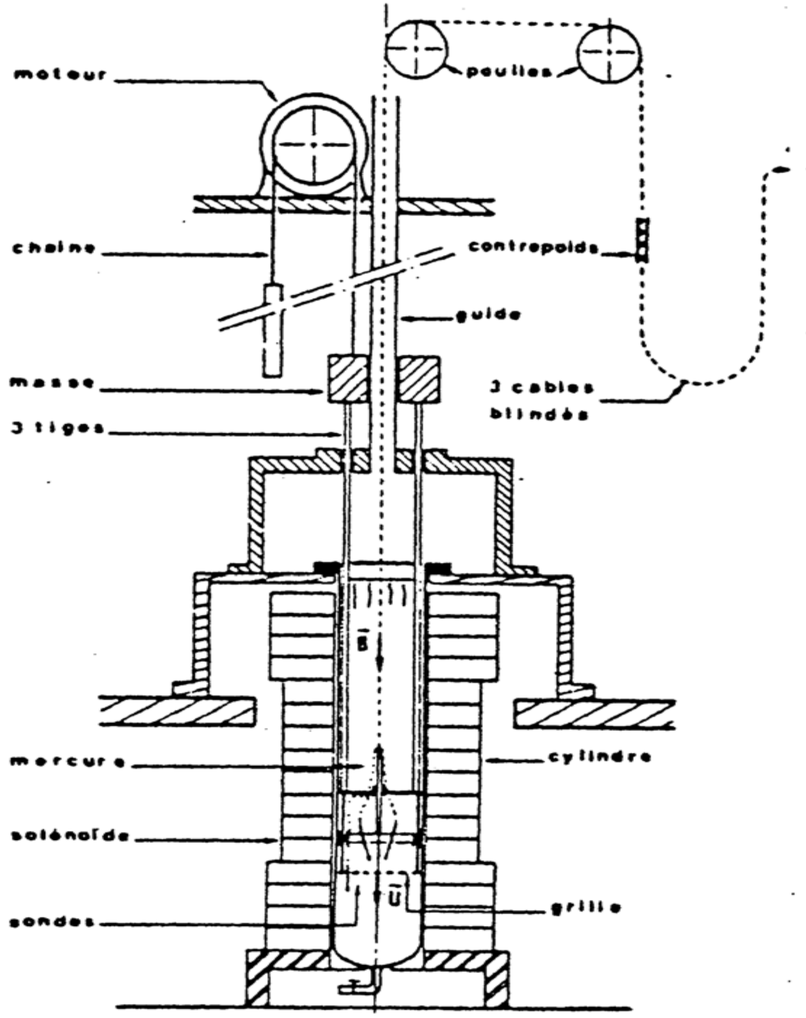
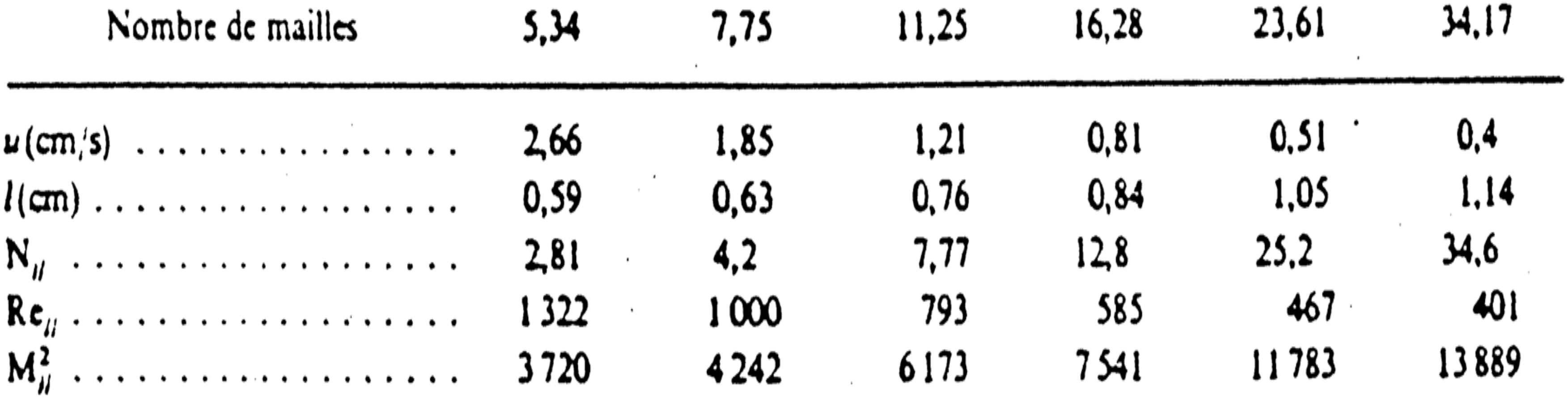


Fig. 2 — Installation expérimentale.

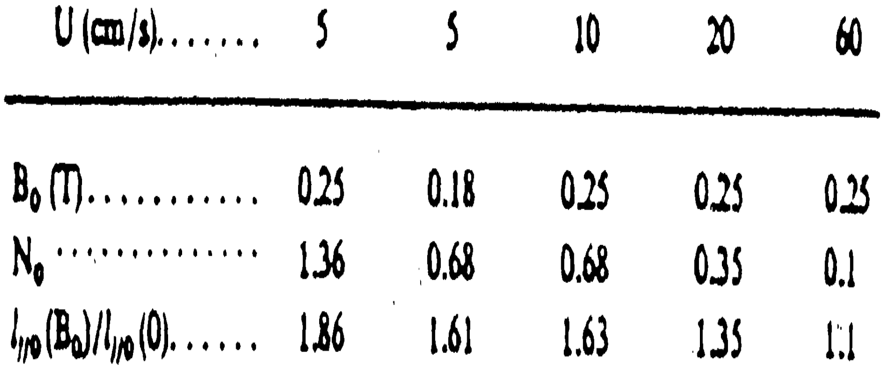
Fig. 2 — Experimental facility.

Evolution des paramètres caractéristiques en fonction de la distance à la grille.

$B = 0{,}4$ T, $Ro = 900$, $No = 1{,}2$



Nombre de mailles	5,34	7,75	11,25	16,28	23,61	34,17
u (cm/s)	2,66	1,85	1,21	0,81	0,51	0,4
l (cm)	0,59	0,63	0,76	0,84	1,05	1,14
$N_{//}$	2,81	4,2	7,77	12,8	25,2	34,6
$Re_{//}$	1 322	1 000	793	585	467	401
$M^2_{//}$	3 720	4 242	6 173	7 541	11 783	13 889



U (cm/s).......	5	5	10	20	60
B_0 (T)...........	0.25	0.18	0.25	0.25	0.25
N_0	1.36	0.68	0.68	0.35	0.1
$l_{//0}(B_0)/l_{//0}(0)$......	1.86	1.61	1.63	1.35	1.1

Evolution of the parallel interaction parameter

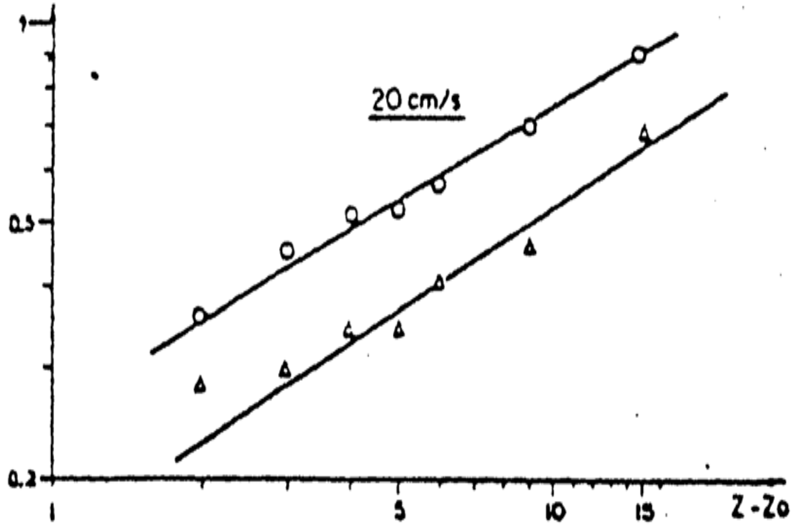


Fig. 4. – Evolution of the parallel integral scale.

PIPE FLOW, || FIELD

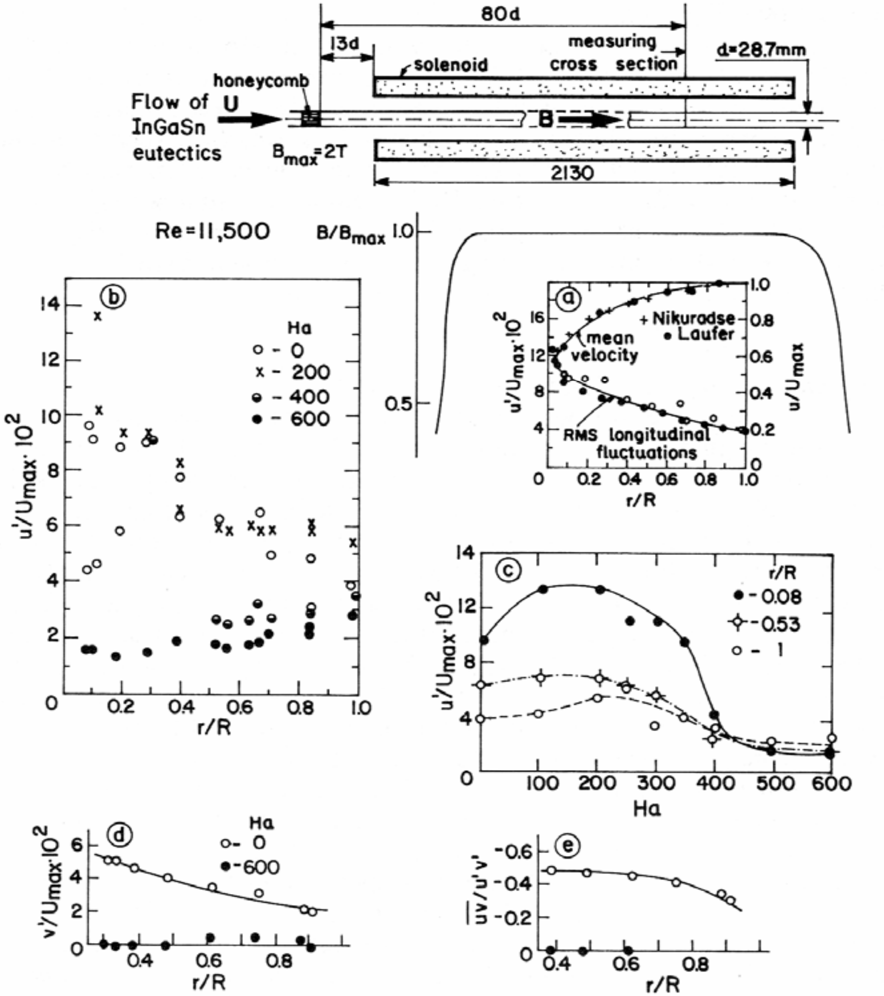
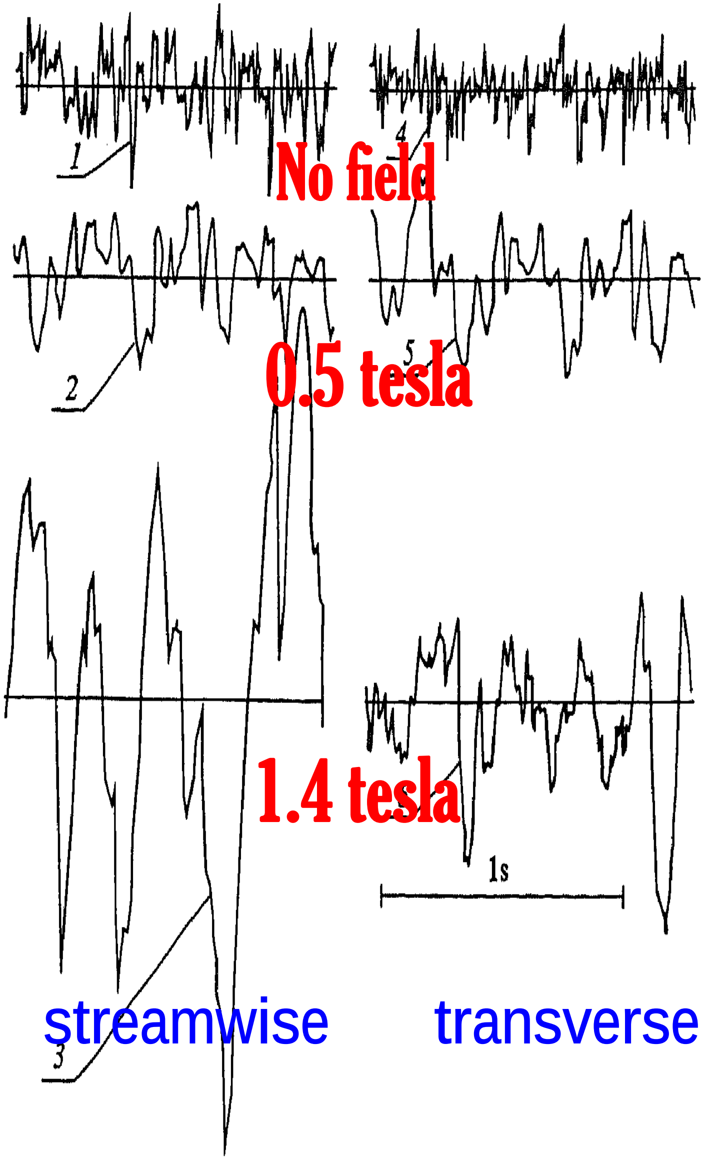


Fig. 15 Experimental results for turbulent flow structure in a longitudinal magnetic field[45]: a) results without a magnetic field; b) radial profiles of rms of longitudinal velocity fluctuations; dependence of rms on c) longitudinal, d) radial velocity fluctuations on Hartmann number; e) correlation coefficient between the longitudinal and radial velocity fluctuations.



No field

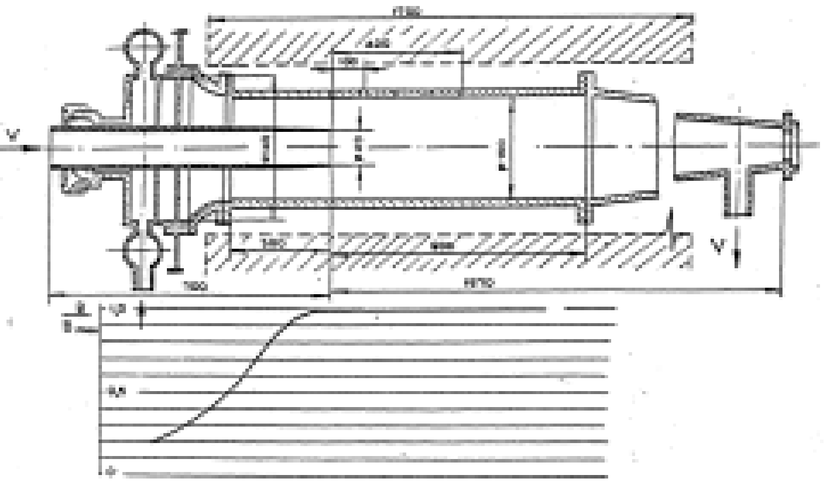
0.5 tesla

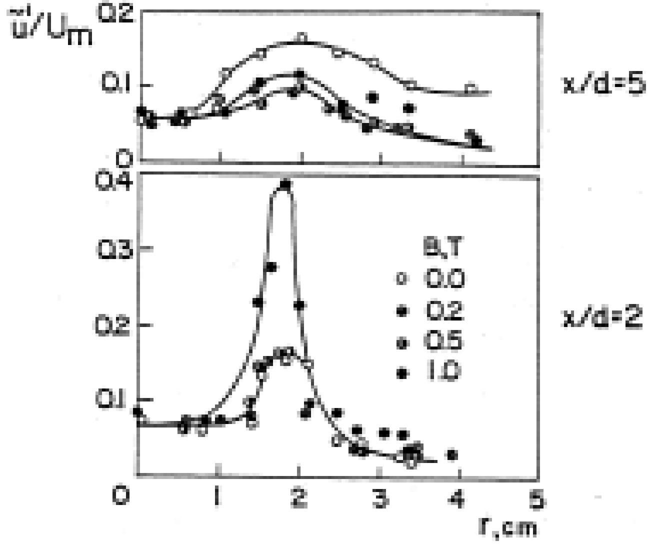
1.4 tesla

streamwise

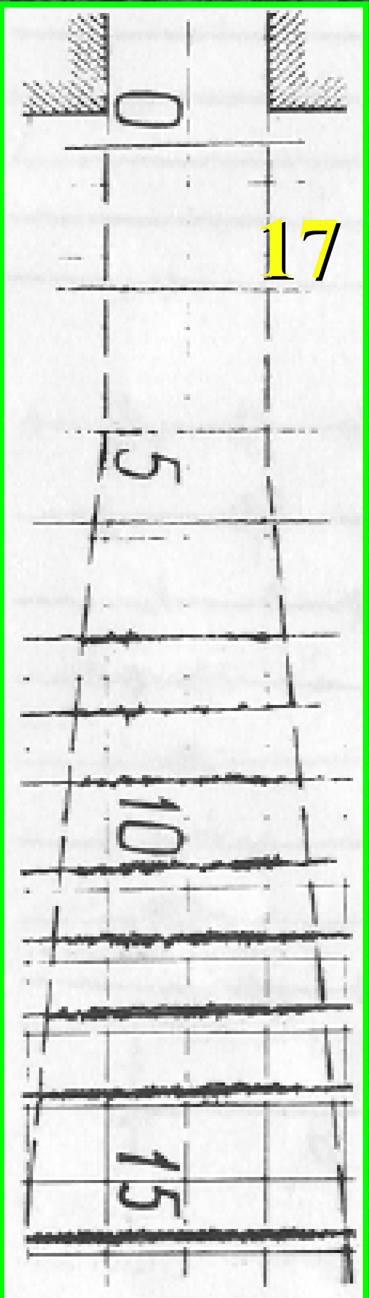
transverse

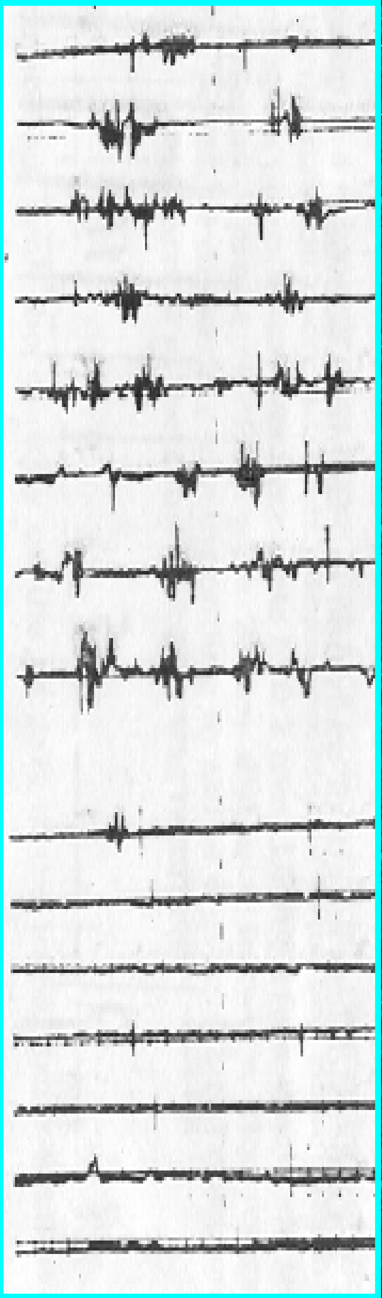
JET , || FIELD





RMS longitudinal fluctuations





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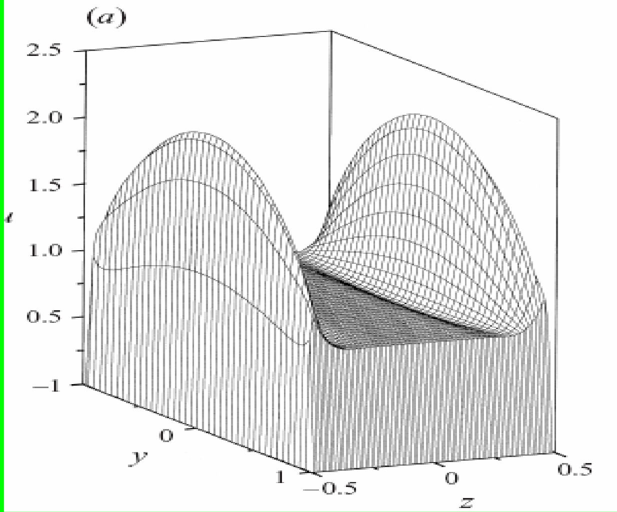
ANISOTROPY - CHANNEL WITH ELECTRICALLY CONDUCTIVE WALLS



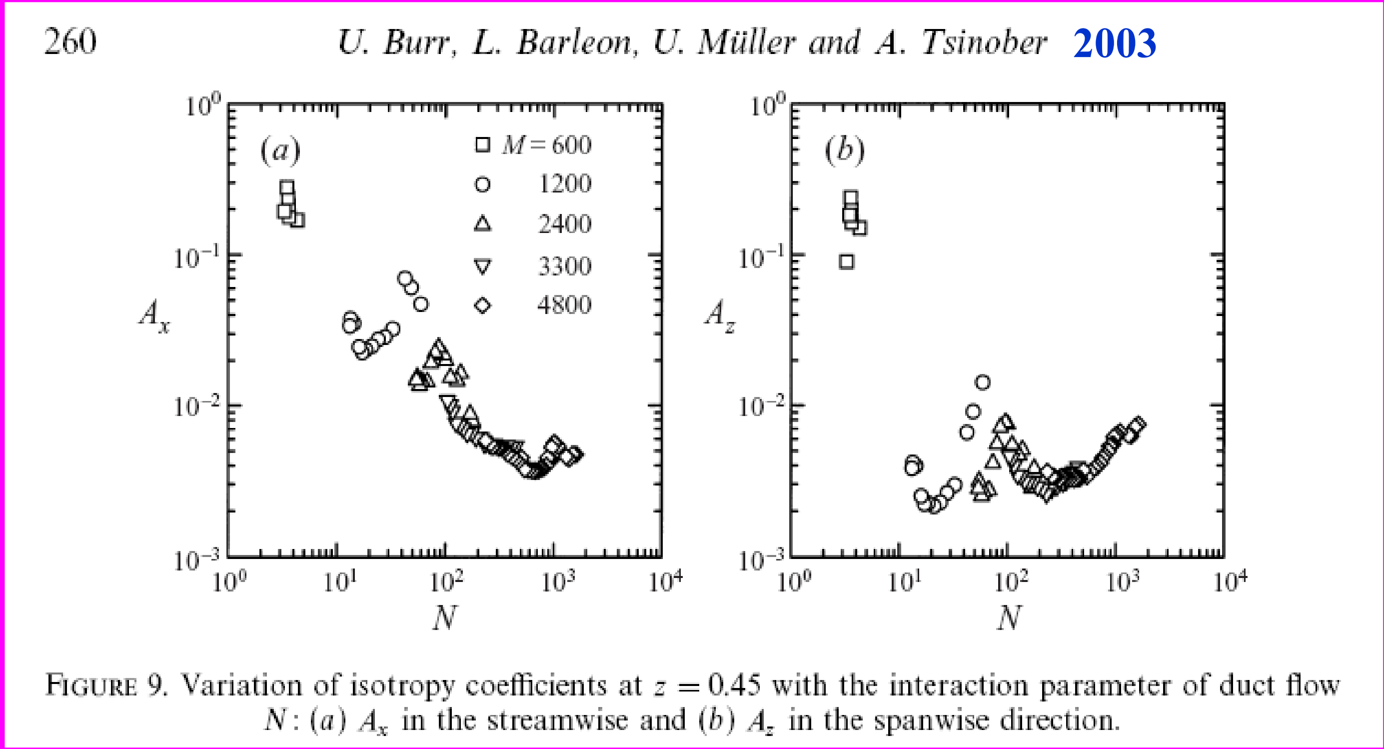


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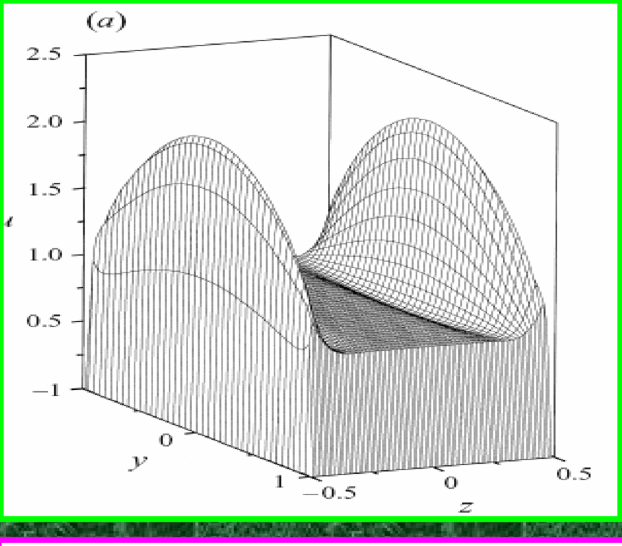
FIGURE 9. Variation of isotropy coefficients at $z = 0.45$ with the interaction parameter of duct flow N: (a) A_x in the streamwise and (b) A_z in the spanwise direction.

$$A_x = \frac{2\overline{(\phi'_y)^2}}{\overline{(\phi'_x)^2}}$$

$$A_z = \frac{2\overline{(\phi'_y)^2}}{\overline{(\phi'_z)^2}}$$

ANISOTROPY - CHANNEL WITH ELECTRICALLY CONDUCTIVE WALLS

Three-D structure of small scales



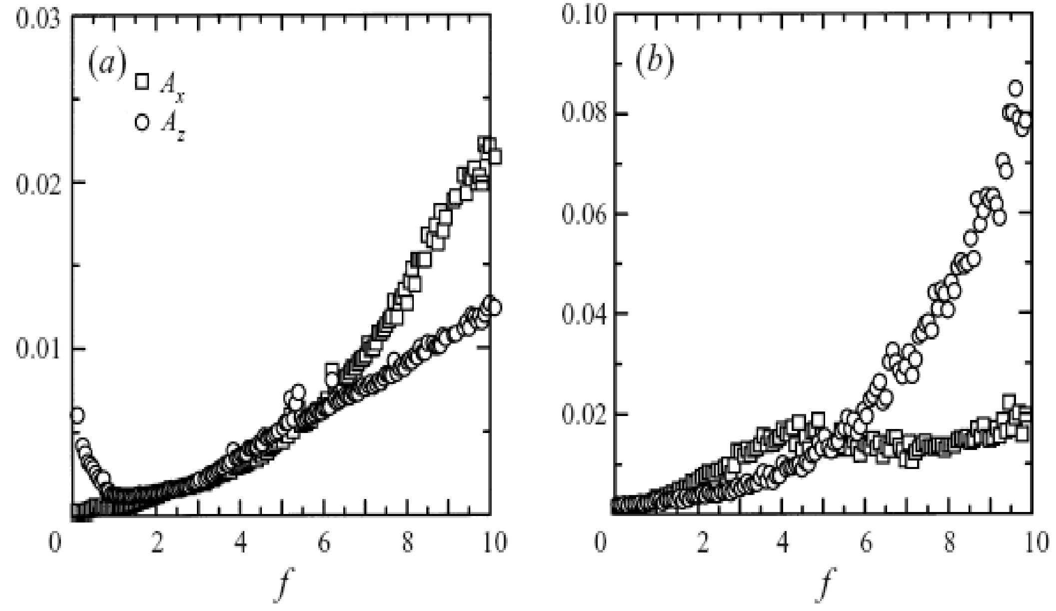


FIGURE 11. Frequency dependence of isotropy coeficients $A_x(f)$ and $A_z(f)$. The signals are recorded at $M = 4800$ close to the sidewall at $z = 0.45$. (*a*) $Re = 3.0 \times 10^4$ and (*b*) $Re = 1.0 \times 10^5$.

$$A_x(f) = \frac{2E_y}{E_x}$$

$$A_z(f) = \frac{2E_y}{E_z}$$

CONVECTION IN A HORIZONTAL MAGNETIC FIELD

Bottom heating

LEHNERT &LITTLE 1957

BURR & MUELLER 2003

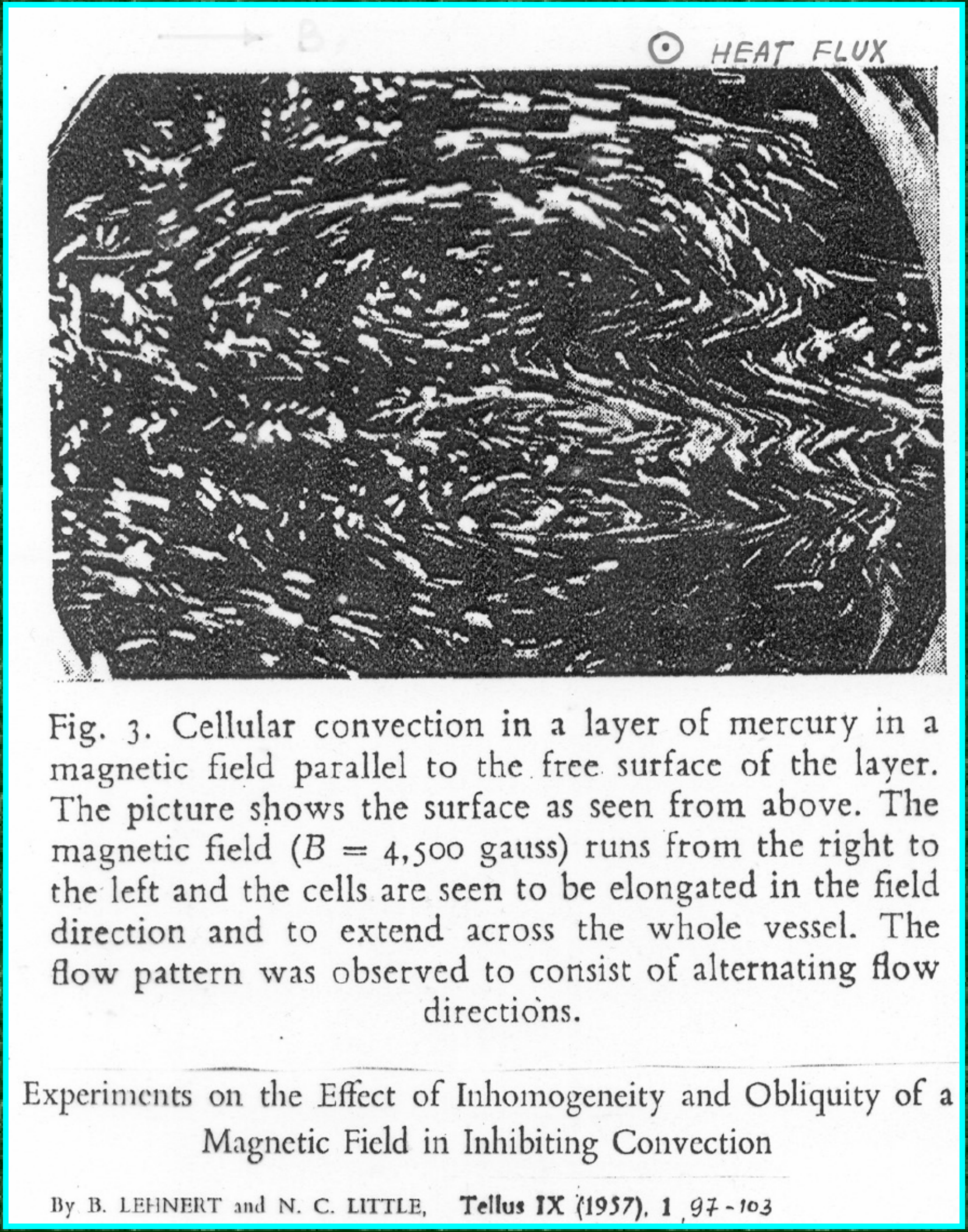


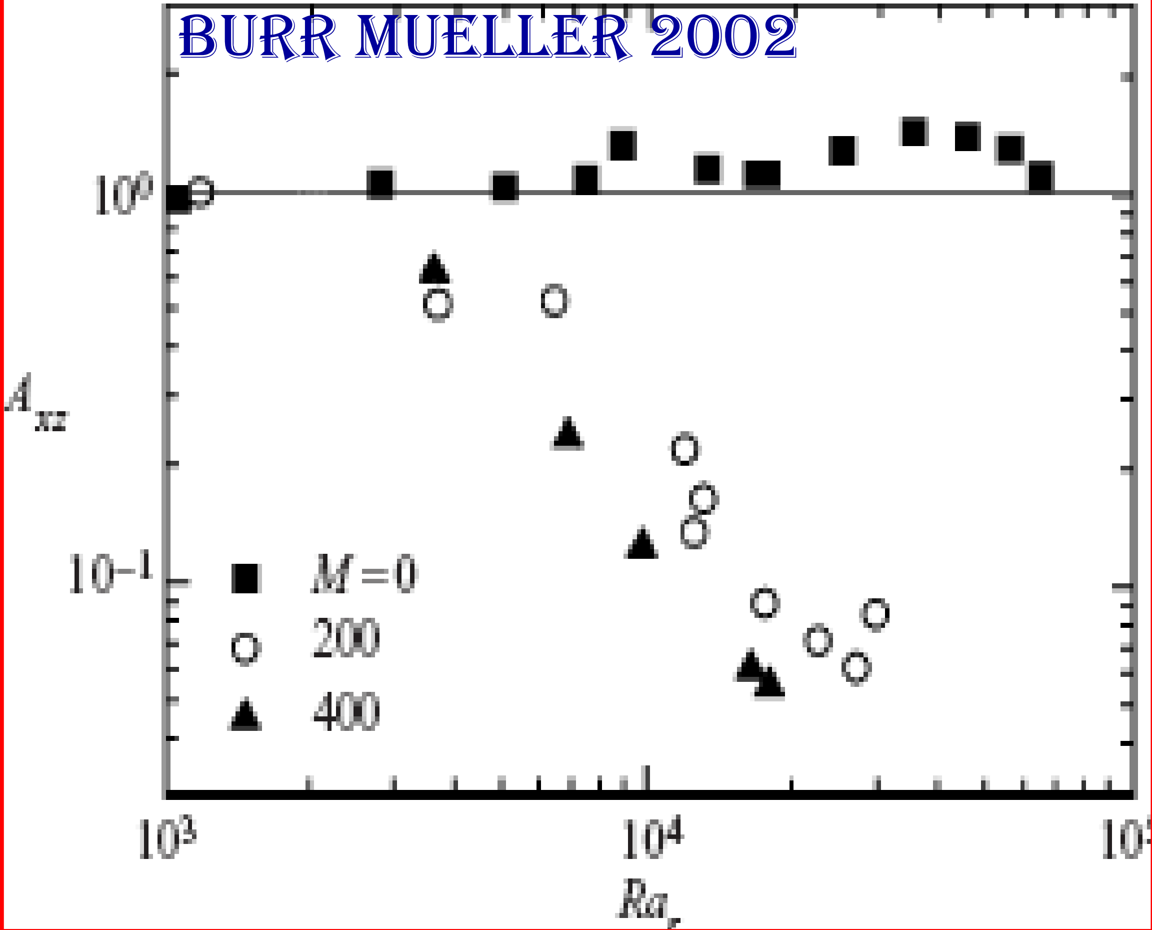
Fig. 3. Cellular convection in a layer of mercury in a magnetic field parallel to the free surface of the layer. The picture shows the surface as seen from above. The magnetic field ($B = 4{,}500$ gauss) runs from the right to the left and the cells are seen to be elongated in the field direction and to extend across the whole vessel. The flow pattern was observed to consist of alternating flow directions.

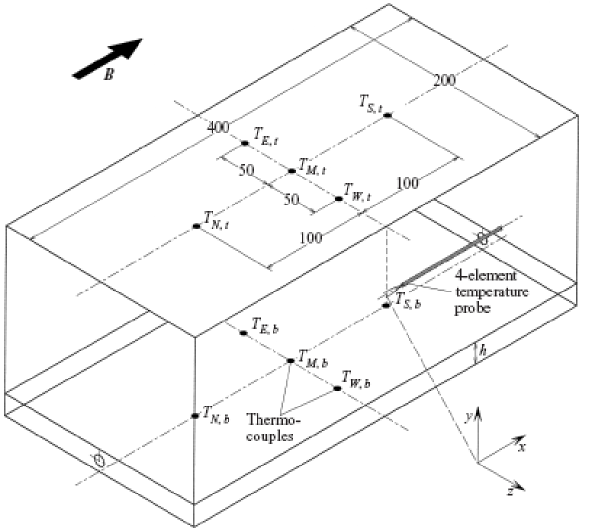
Experiments on the Effect of Inhomogeneity and Obliquity of a Magnetic Field in Inhibiting Convection

By B. LEHNERT and N. C. LITTLE, **Tellus IX** (1957), **1** , 97 - 103

Transition of the three dimensional convective roll pattern into a quasi-two-dimensional flow pattern in such a way that convective rolls become more and more aligned with the magnetic field.

ANISOTROPY CONVECTION IN A HORIZONTAL MAGNETIC FIELD


BURR MUELLER 2002



$$A_{xz} = \frac{\overline{(\partial_x T_P)^2}}{\overline{(\partial_z T_P)^2}}$$

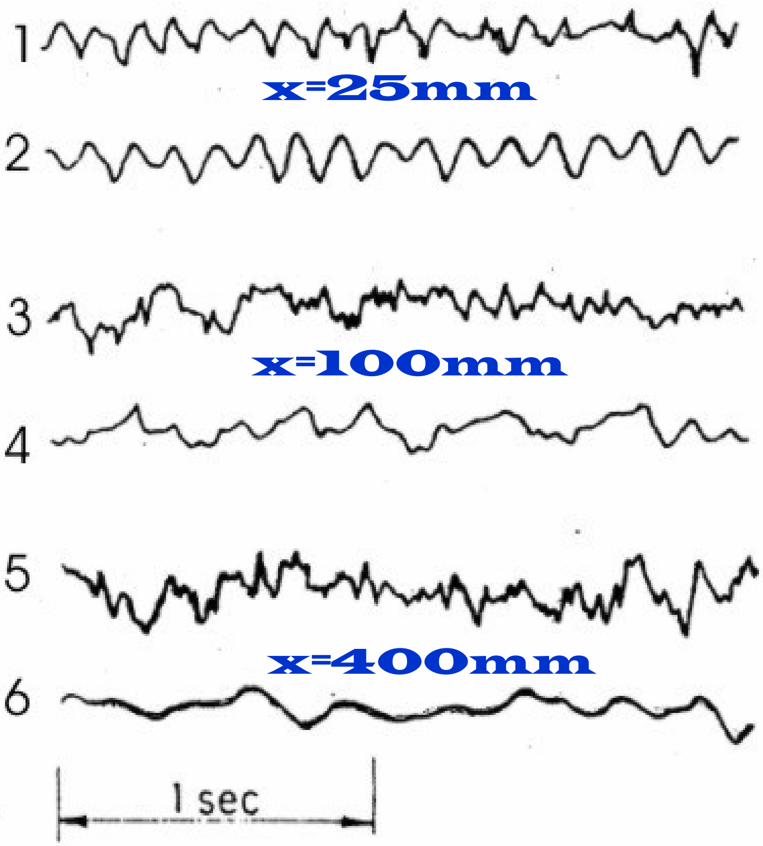
Horizontal isotropy coefficent A_{xz} plotted versus a reduced Rayleigh number $Ra_r = Ra - Ra_t$ for Hartmann numbers $M = 0$, 200 and 400.

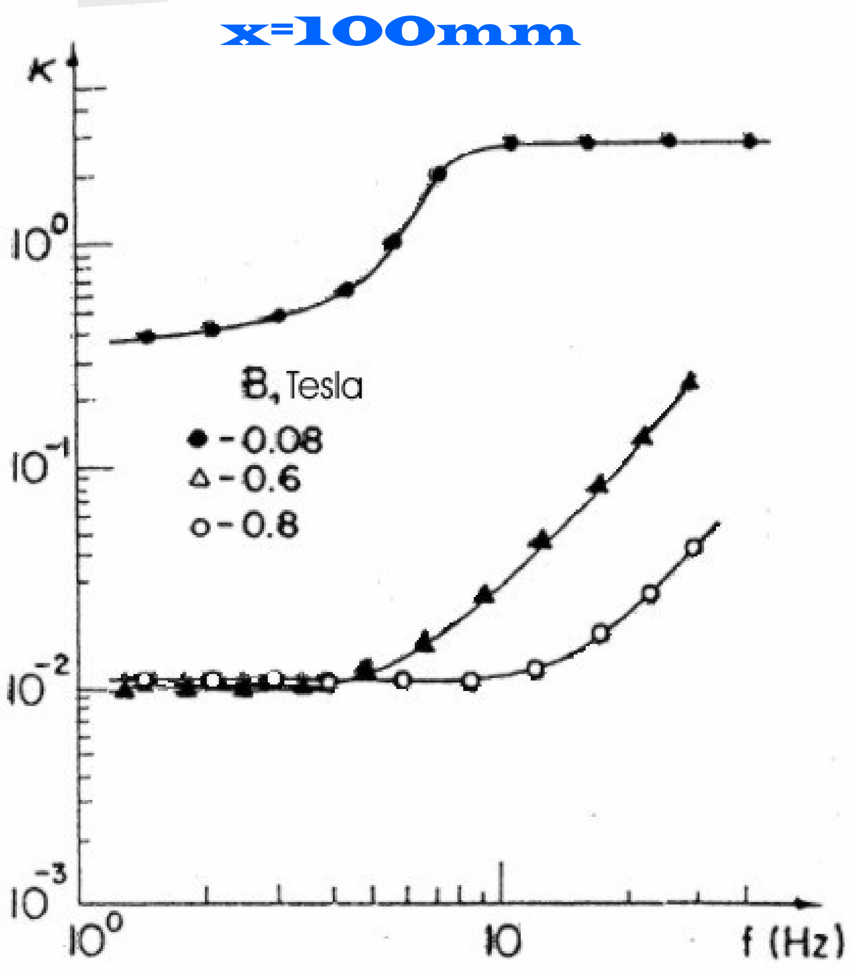
THREE-D STRUCTURE OF SMALL SCALES

Mercury flow in the wake (centerline) of circular cylinder d=5mm in ⊥ magnetic field

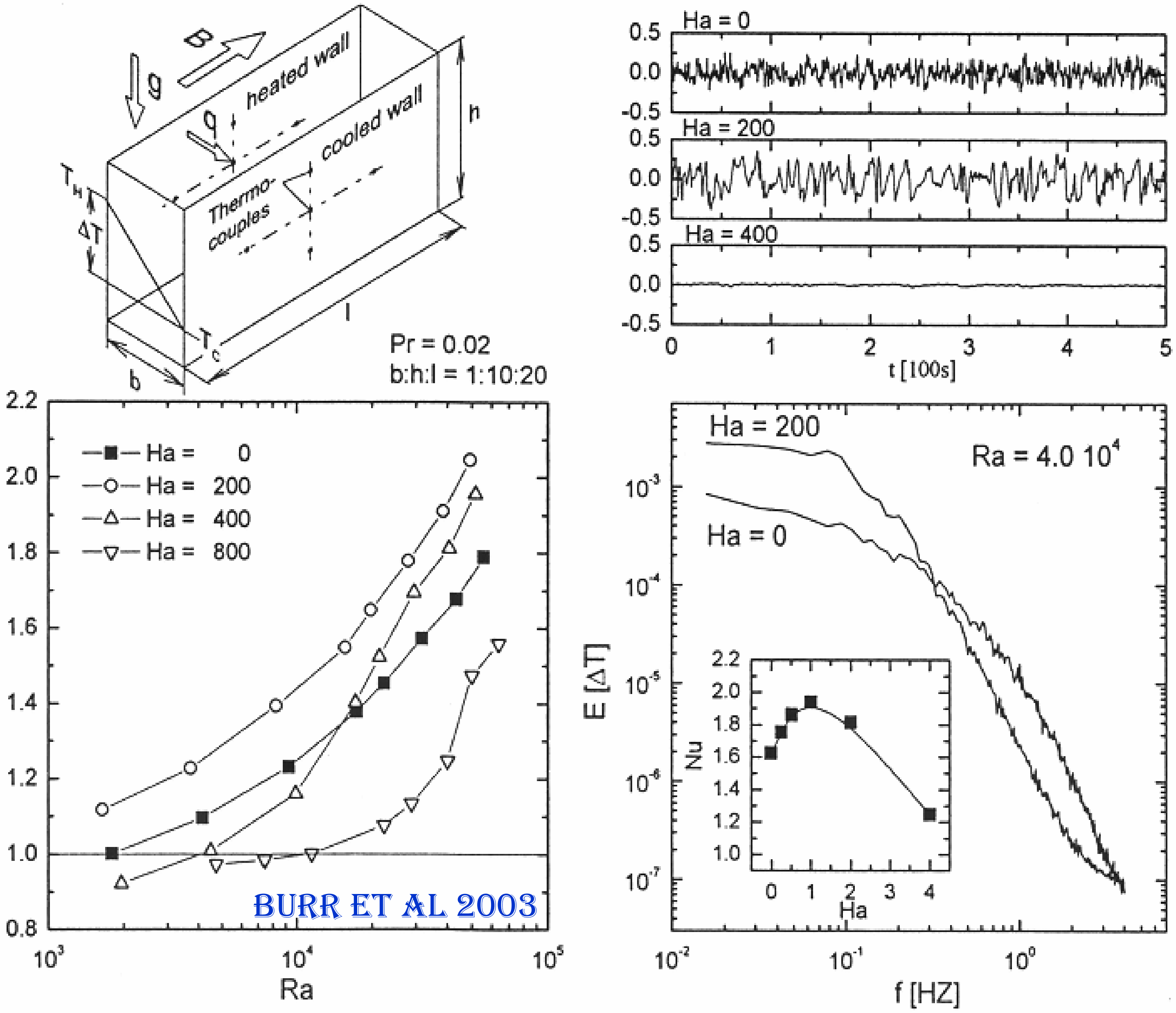
Ratio of spectral densities of $\nabla\varphi_{||}$ and $\nabla\varphi_{\perp}$

1, 3, 5 – 0.08 Tesla;
2, 4, 6 – 0.8 Tesla;





CONVECTION IN A VERTICAL SLOT



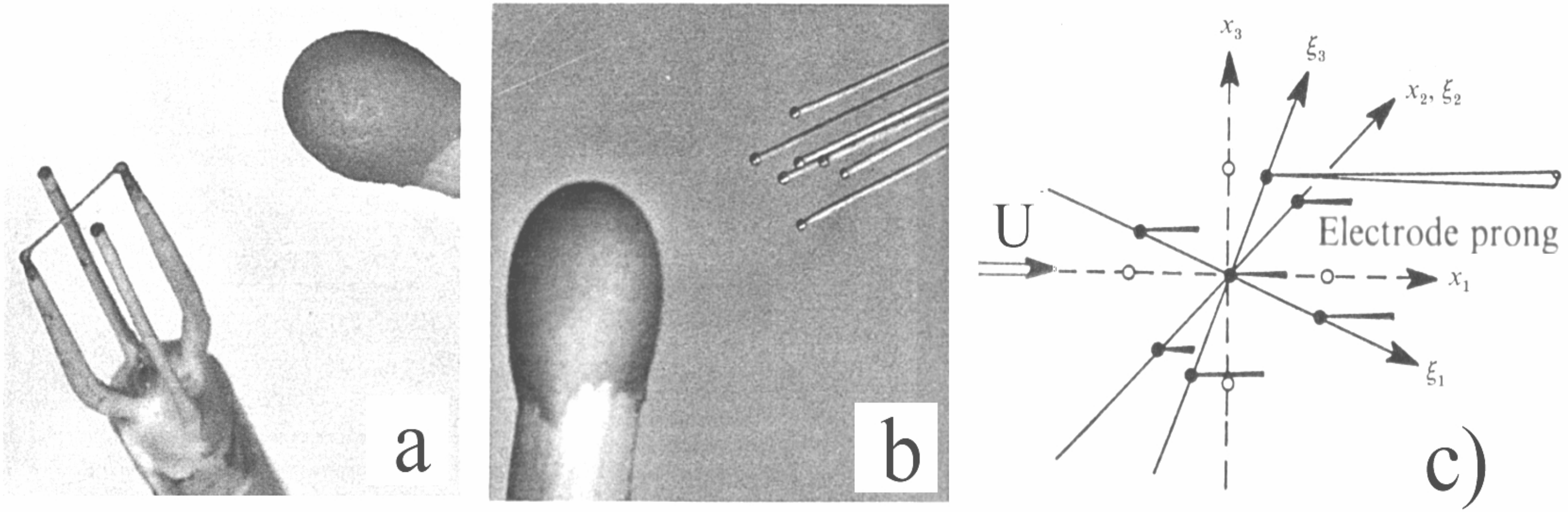
BURR ET AL 2003

POTENTIAL GRADIENT $\nabla\varphi$ VERSUS VELOCITY $\mathbf{u}$

$\mathbf{j} = \sigma\{-\nabla\varphi + \mathbf{u}\times\mathbf{B}\}$ FARADAY 1832, $\nabla\varphi\neq\mathbf{u}\times\mathbf{B}$

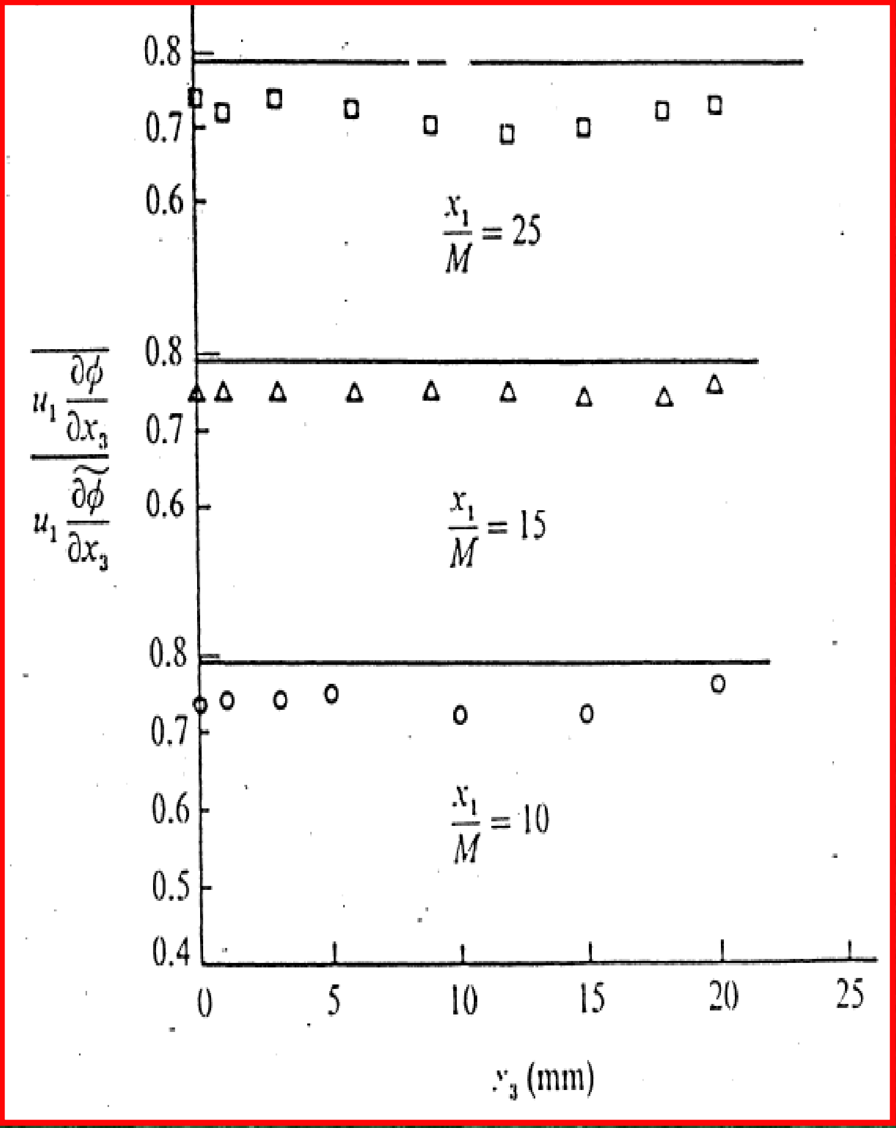
$\nabla^2\varphi = \omega_{||B}$; GROSSMAN, LI & EINSTEIN (JR.), 1958

TSINOBER ET AL 1987



FLOW OF ELECTROLYTE

Pure kinematics, TSINOBER ET AL 1987



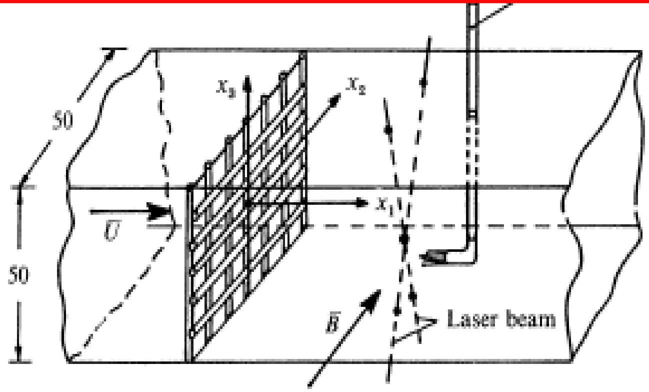


FIGURE 1. Schematic of the experimental arrangement of the test section.

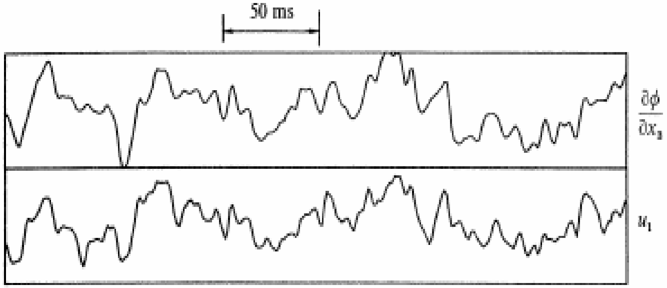


FIGURE 7. An example of oscillograms of the u_1 signal measured by a wire hot-film probe and of the $\partial\phi/\partial x_3$ signal measured by the potential-difference probe.

$$\overline{u_1 \frac{\partial\phi_2}{\partial x_3}} \Big/ \tilde{u}_1 \widetilde{\frac{\partial\phi_2}{\partial x_3}} = \tfrac{1}{2}(2.5)^{\frac{1}{2}} = 0.79$$

PROBES WITH LOCAL MAGNETIC FIELD

CRAMER ET AL 2006

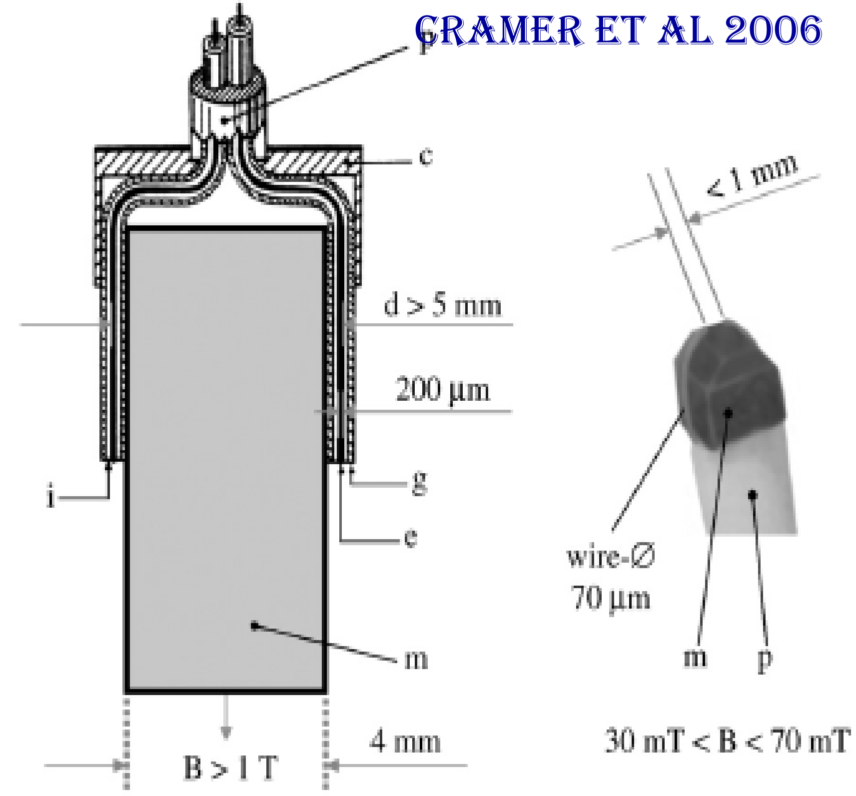


Fig 4. Schematic diagram of the probe :
(p) probe-holder, (c) jacket, (e) wire core,
(g) conductor sheaths, (i) insulator,
(m) permanent magnet, (Δ) revolution axis.

WEISSENFLUH 1985

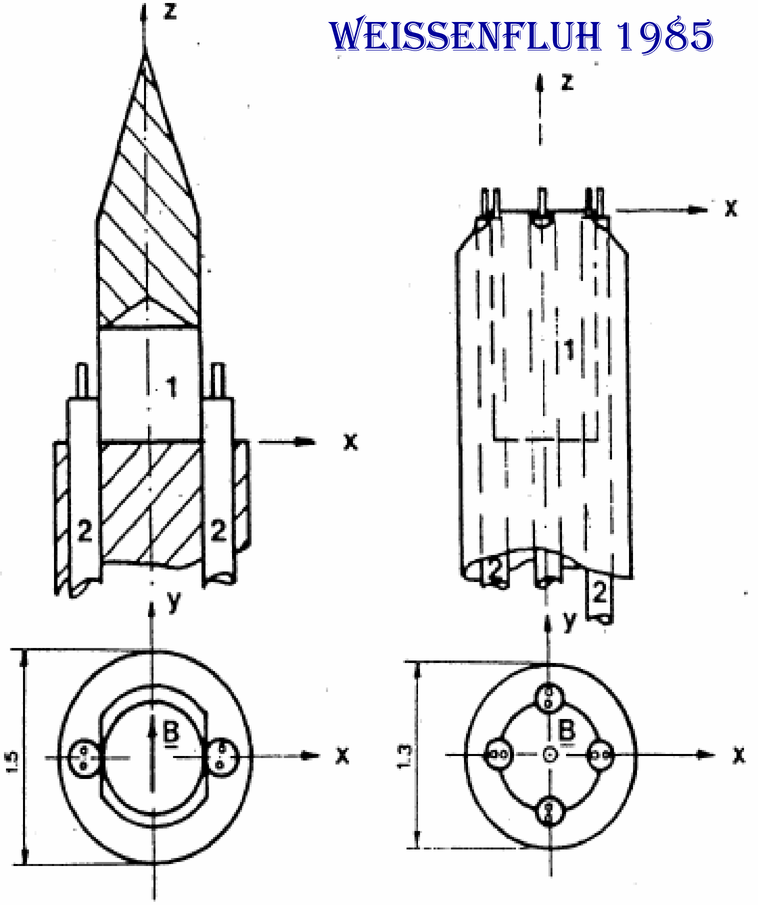


FIG. 1. (a) Axial velocity probe; (b) transverse velocity probe. (1) Rare-earth permanent magnet (RECOMA), (2) open-ended chromel–alumel thermocouple, **B** magnetic field direction.

ASYMPTOTIC BEHAVIOR IN STRONG MAGNETIC FIELDS I

QUASI-TWO-DIMENSIONAL FLOWS

We may say that the two-dimensional flow "does not see" a uniform field. In a strong external field, the turbulence degenerates just into this two-dimensional form.

LANDAU AND LIFSHITZ , 1981

But is ε in

Quasi-2D = Pure 2D + ε

always small ?

TSINOBER 1996, 2001*

Or how close is Q2D MHD turbulence to the P2D one and in what sense?

*See pp. 216-218 in Tsinober, A. (2001) An informal introduction to turbulence and ref . 23 in Moreau, Thess, Tsinober, (2006)

ASYMPTOTIC BEHAVIOR AT STRONG MAGNETIC FIELDS II

Multiplicity of Q2D- states

due to essentially nonlocal nature of the electromagnetic force and thereby much stronger influence of BC's :

Examples, not exaustive

- Inertialess regime in flows in the presence of Hartmann walls
- Nonlinear regime in azimuthal configuration, i.e. without Hartmann walls
- Intermediate asymptotics
- ??? Layer like structure (as in stratified flows)
- All/some of the above are different from PURE 2D-NONLINEAR (i.e. without magnetic field at the outset) regime ???

ASYMPTOTIC BEHAVIOR III

Are MHD Q2D flows low dissipative?

$$D\mathbf{u}/Dt = -\nabla p + \nu\nabla^2\mathbf{u} - (\sigma/\rho)B_0^2\nabla^{-2}\{\partial^2\mathbf{u}/\partial x^2{}_B\}$$

∇^{-2} – is an inverse Laplace operator (nonlocality an BC's)

or

$$D\mathbf{u}/Dt = -\nabla p + \nu\nabla^2\mathbf{u} - {}_{w\nabla}(\sigma/\rho)B_0^2\{-\nabla\varphi + \mathbf{u}\times\mathbf{B}\}\times\mathbf{B}$$

$$\nabla^2\varphi = \mathbf{B}\cdot\text{curl}\boldsymbol{\omega}$$

As $B_0 \rightarrow \infty$ both $\partial\mathbf{u}/\partial x_B$ and $\{-\nabla\varphi + \mathbf{uxB}\} \rightarrow 0$

But what happens with $(\sigma/\rho)B_0^2\Delta\text{-}1\{\partial^2\mathbf{u}/\partial x^2{}_B\}$ and $(\sigma/\rho)B_0^2\{-\nabla\varphi + \mathbf{u}\times\mathbf{B}\}\times\mathbf{B}$? Can they and/or Joule dissipation remain finite as $B_0 \rightarrow \infty$? Is it possible that the limit is singular?

AN EXAMPLE OF LINERIZATION

FLOW IN HALF-SPACE, *Tsinober 1973*

$$u_k = u_{sk} - \frac{1}{Ha}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty} u_i u_j \frac{\partial G_{ik}^*}{\partial \eta_j} d\eta_1 d\eta_2 d\eta_3$$

$$\nabla^2 \mathbf{u}_s + Ha^2\left(-\nabla\varphi_s + \mathbf{u}_s \times \mathbf{B}\right) - \nabla p_s = 0\,,$$

$$\operatorname{div}\,\mathbf{u}_s = 0\,,\ \nabla^2\varphi_s = \mathbf{B}\cdot \operatorname{rot}\,\mathbf{u}_s$$

AZIMUTHAL MAGNETIC FIELD

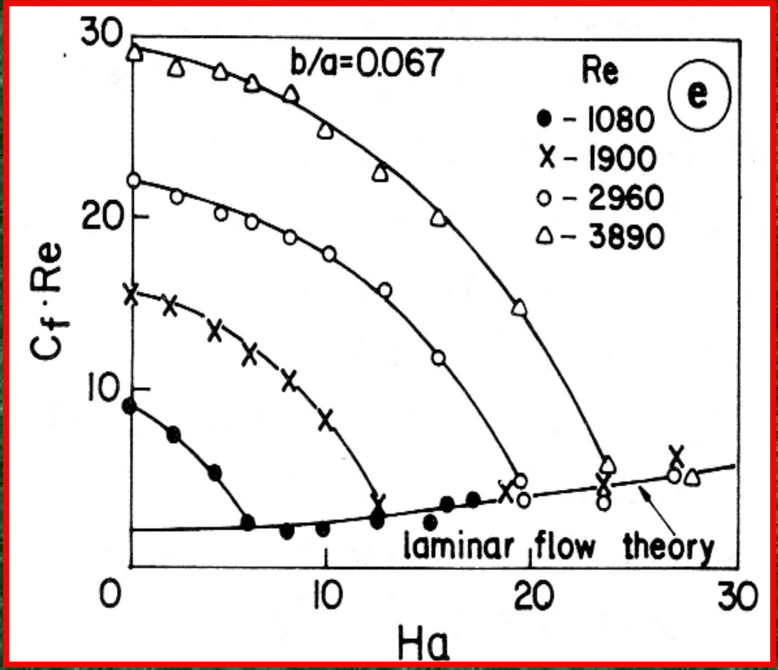
No Hartmann walls

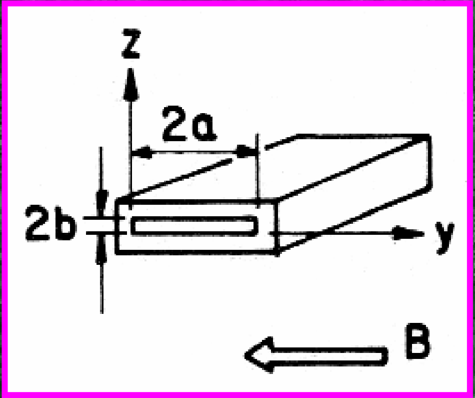
> We may say that the two-dimensional flow "does not see" a uniform field. In a strong external field, the turbulence degenerates just into this two-dimensional form. LANDAU AND LIFSHITZ , 1981

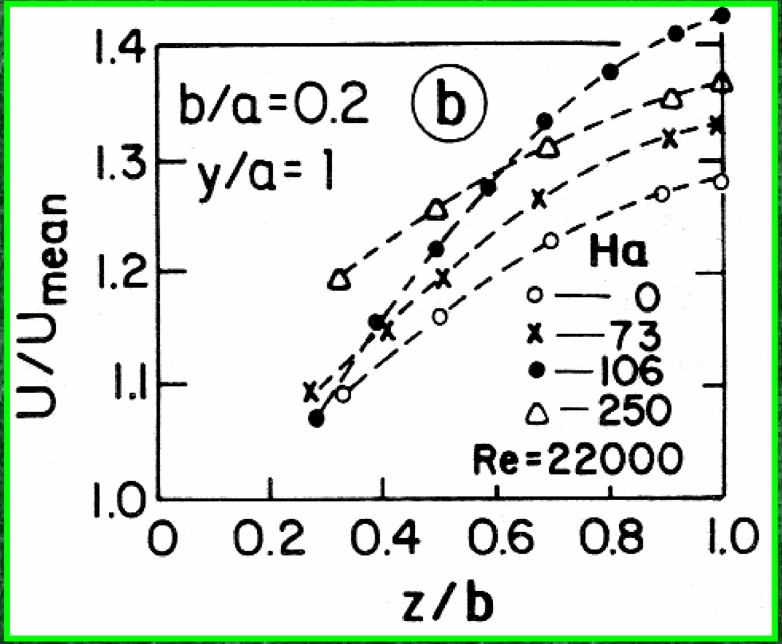
Flows in such configurations (i.e. *without* Hartmann walls) are of particular interest due to the well known fact that a pure 2D flow does not interact with a homogenous magnetic field orthogonal to the plane of the flow. In other words, the 2D flow in such a configuration is a solution of the ordinary Navier-Stokes equations at arbitrary Rm.

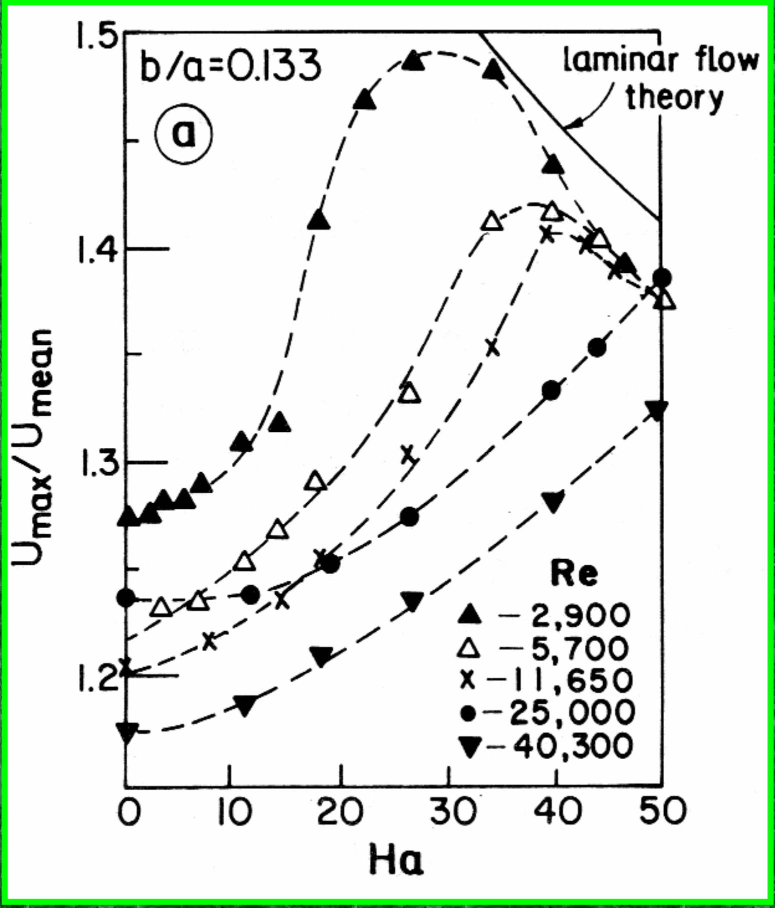
The cleanest way to observe the process of two-dimensionalization can be achieved in the total absence of the Hartmann walls. Experimentally this can be done in an axi-symmetric configuration with an azimuthal magnetic field in the form B □ r. Such a not curl-free field can be realized by applying an uniform electric current by means of electrodes located up/downstream of the working section with the expectation that their influence on the flow in the working section would be negligible (Tsinober 1990)

ARE Q2D MHD FLOWS LOW DISSIPATIVE?





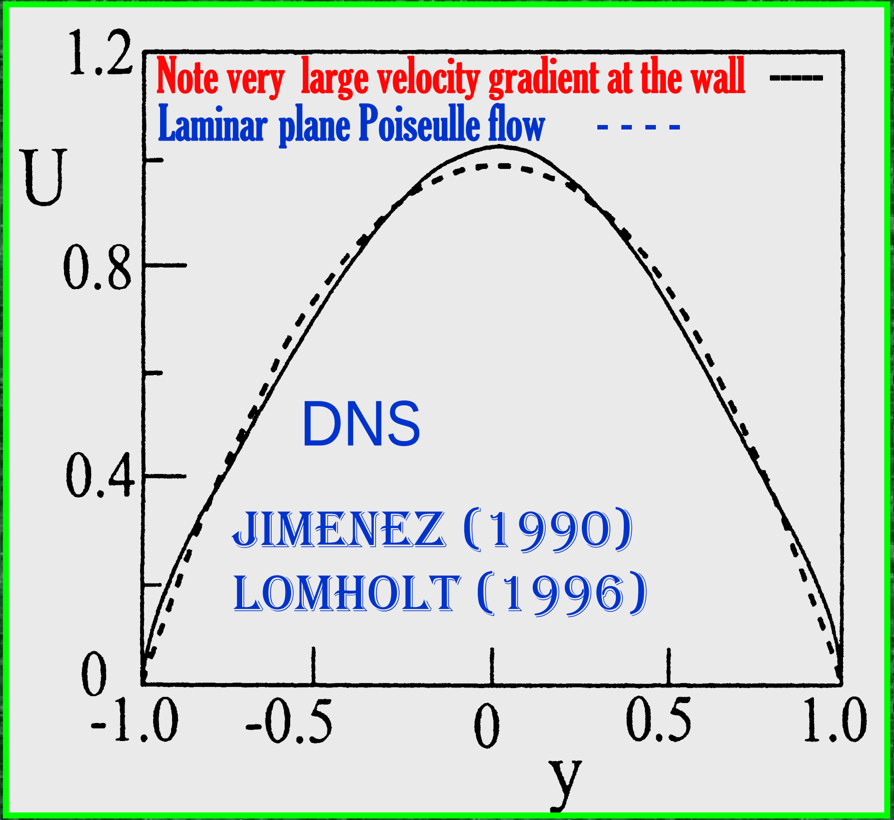


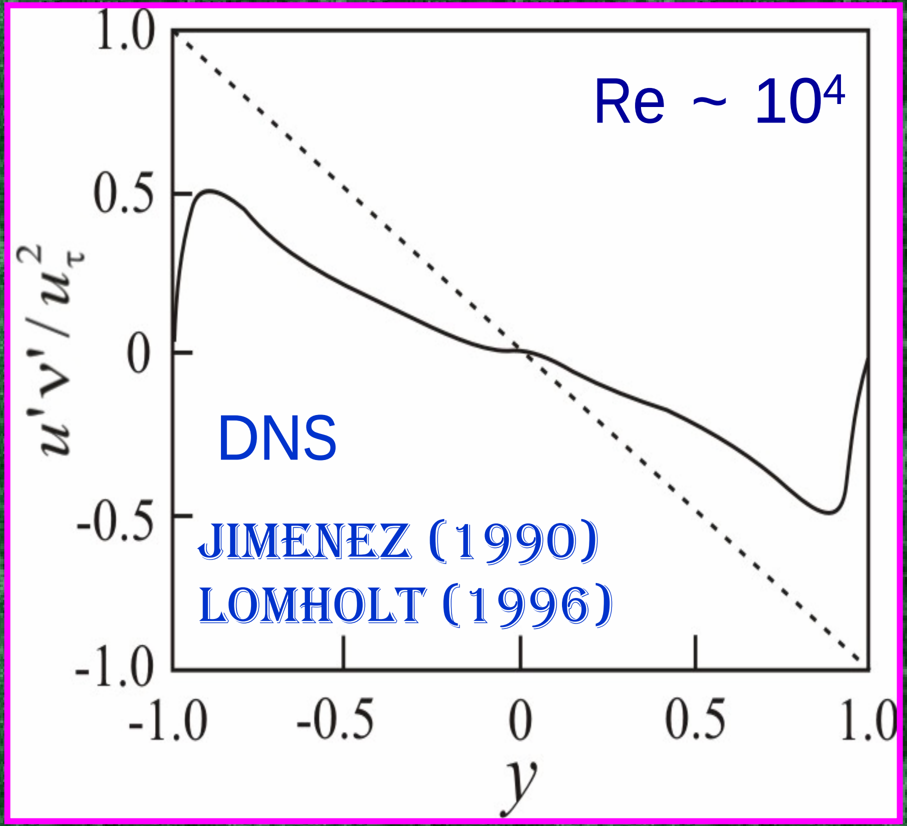


AZIMUTHAL CONFIGURATION

PURE 2D TURBULENT PLANE POISEUILLE FLOW

Drag is about **twice larger** than the purely laminar value and is only **twice smaller** than its value for the 3D turbulent flow, i.e. P2D plane Poiseulle turbulent flow is not that low dissipative. Moreover, the Reynolds stresses in this flow are not small either and contribute about a half to the total stress.





ANISOTROPY IS DIVERSE

Q2D MHD turbulent flows created in different conditions may be essentially qualitatively different, e.g. inertialess and nonlinear and different from pure two-dimensional flows.

The problem of the relation(s) between Q2D and P2D turbulent flows is complicated further by the multiplicity of Q2D states: there exist several Q2D flows such as flows in rotating frames, flows with stable density stratification, MHD-flows and some others, which along with being similar kinematically (geometrically) in many respects are very different dynamically. There is little doubt about the qualitative difference between Q2D states produced by physically different processes, e.g. the ones in MHD are of dissipative nature (Joule dissipation), whereas those with rotation are not. Strong anisotropy is a necessary condition only for Q2D and/or low dissipative behavior, e.g. shear turbulent flows with strong shear are both strongly anisotropic and strongly dissipative. Similarly, strong correlations along some direction, i.e. Q2D behavior, do not exclude the possibility of vorticity stretching in this direction.

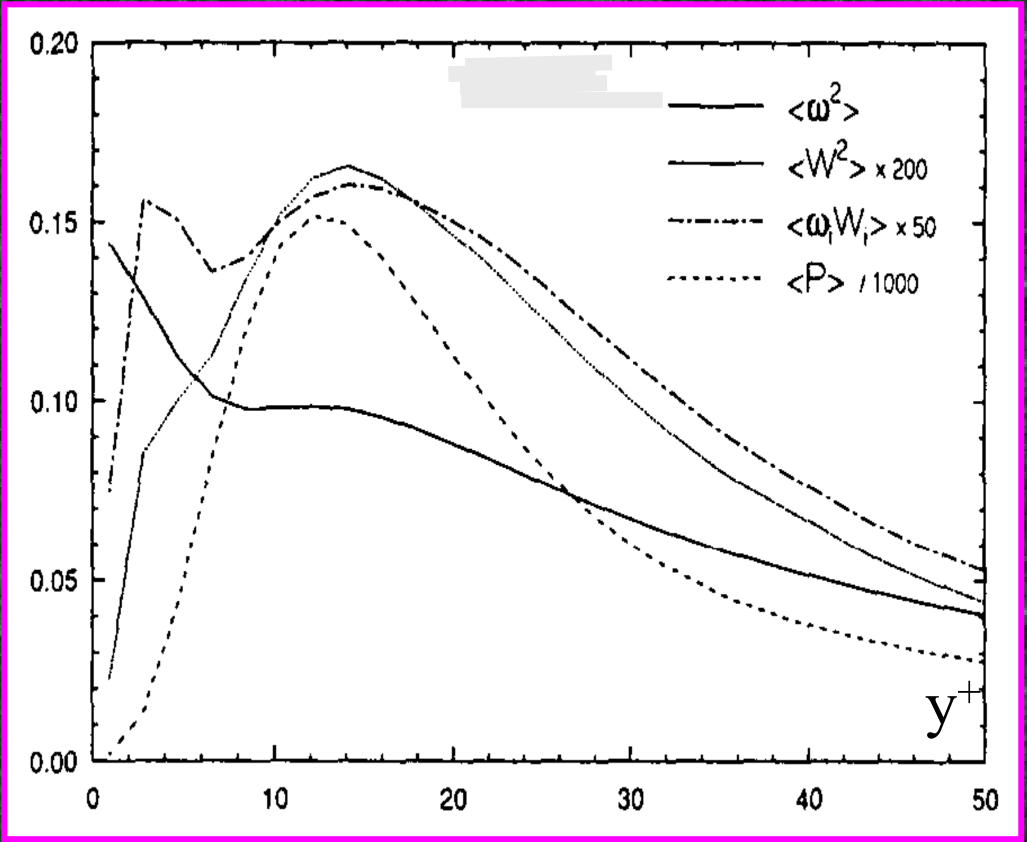
See pp. 216-220 in A. Tsinober (2001) In informal introduction to turbulence, Kluwer

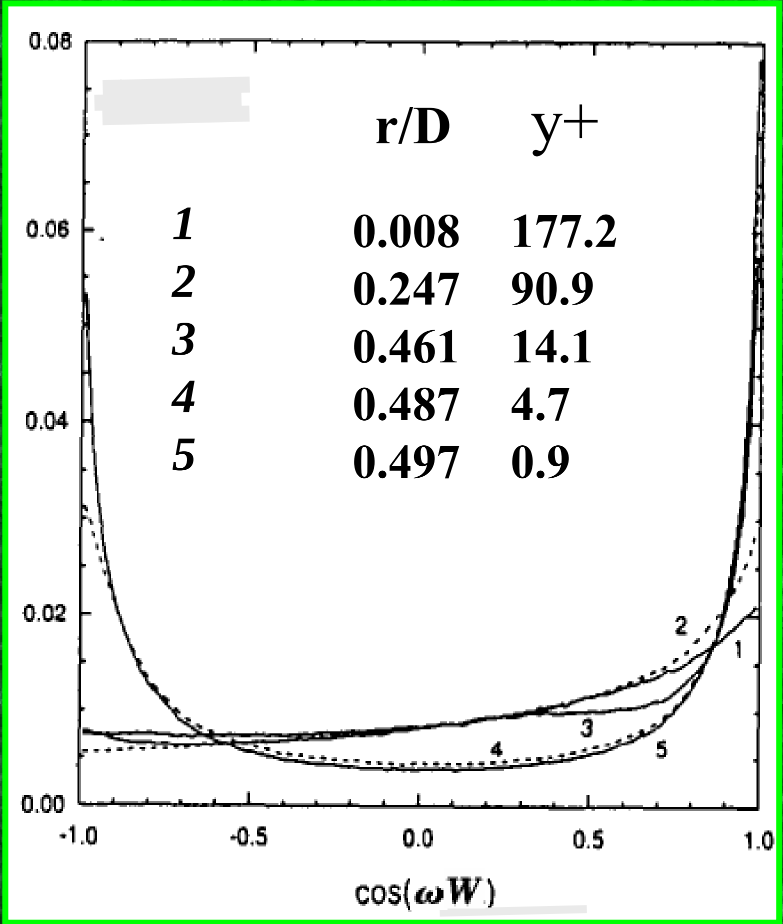
PROFOUND ANALOGIES?

A word of caution

It is rather popular to refer to analogy with the cases of stratified, rotating, or highly strained turbulence as well as some other and, of course, purely two dimensional . However, these analogies are at best kinematical and cannot be seen as “profound” as some authors claim. There are many essential qualitative differences: strongly anisotropic (Q2D) turbulent are qualitatively diverse.

ANISOTROPY - PIPE FLOW





	r/D	y+
1	0.008	177.2
2	0.247	90.9
3	0.461	14.1
4	0.487	4.7
5	0.497	0.9

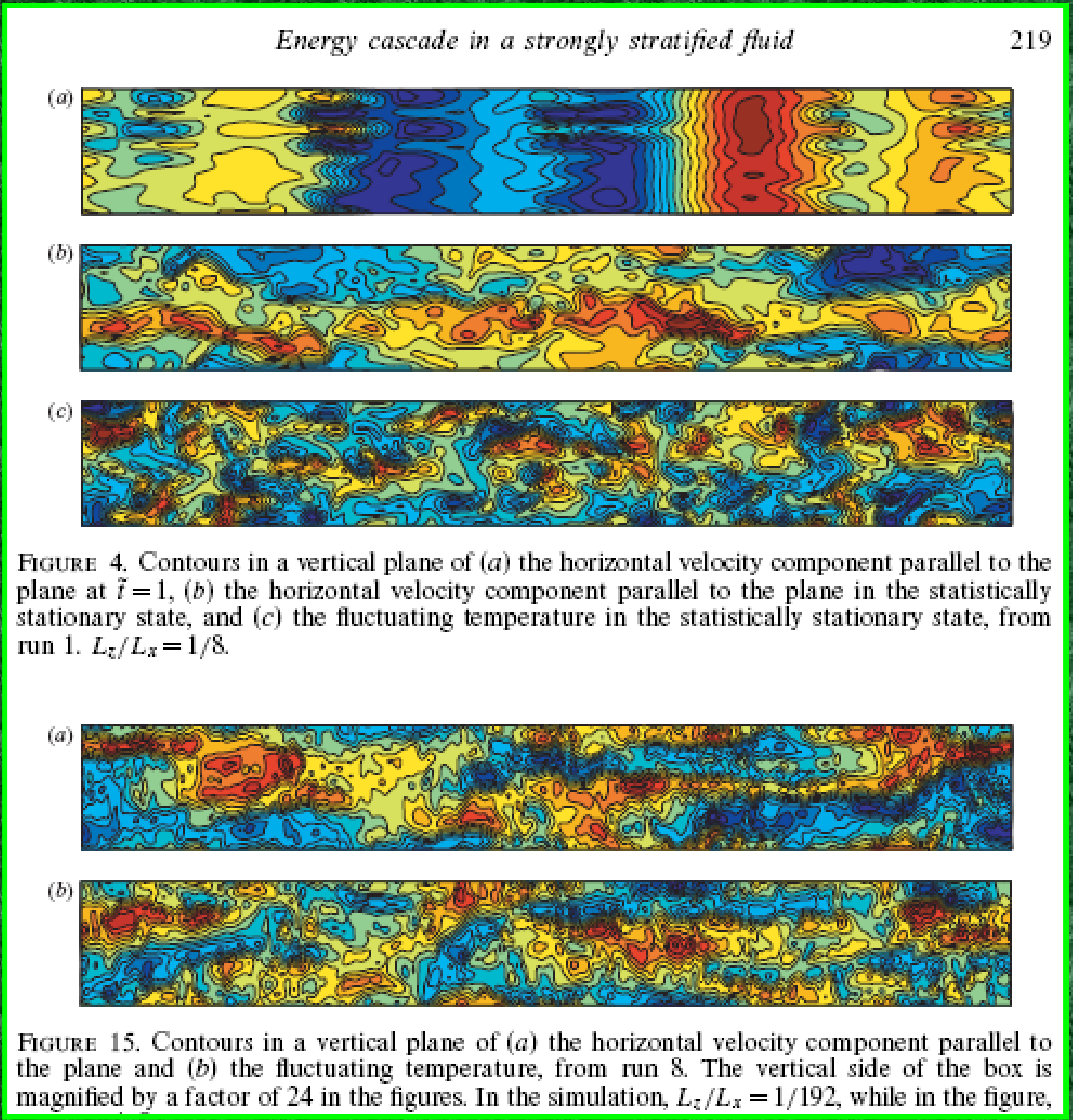
Left

Radial distributions of $\langle\omega_i\omega_i\rangle$, $\langle W^2\rangle$ $(W_i = \omega_j s_{ij})$, $\langle\omega_i\omega_j s_{ij}\rangle$ and turbulent energy production $P = \langle v_r v_z\rangle \mathrm{d}U_z/\mathrm{d}r$

Right

PDF's of the cosine of the angle between vorticity and the vortex stretching vector for different radial positions

LAYERS IN STRONGLY STABLY STRATIFIED FLOWS



Energy cascade in a strongly stratified fluid 219

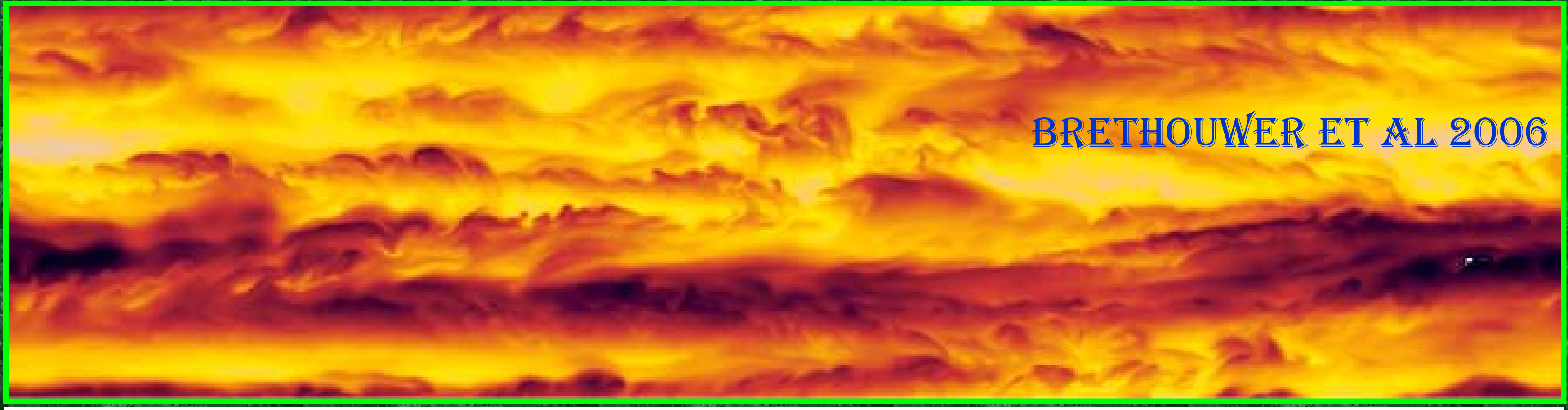
FIGURE 4. Contours in a vertical plane of (*a*) the horizontal velocity component parallel to the plane at $\tilde{t}=1$, (*b*) the horizontal velocity component parallel to the plane in the statistically stationary state, and (*c*) the fluctuating temperature in the statistically stationary state, from run 1. $L_z/L_x=1/8$.

FIGURE 15. Contours in a vertical plane of (*a*) the horizontal velocity component parallel to the plane and (*b*) the fluctuating temperature, from run 8. The vertical side of the box is magnified by a factor of 24 in the figures. In the simulation, $L_z/L_x=1/192$, while in the figure,

LINDBORG 2006

Herring J. R. & M´etais, O. 1989 Numerical experiments in forced stably stratified turbulence. J. Fluid Mech. **202**, 97–115.

LAYERS IN STRONGLY STABLY STRATIFIED TURBULENT FLOWS



BRETHOUWER ET AL 2006

Figure 13: Snapshots of the density fluctuations in a vertical plane for $F_h \simeq 0.015$.

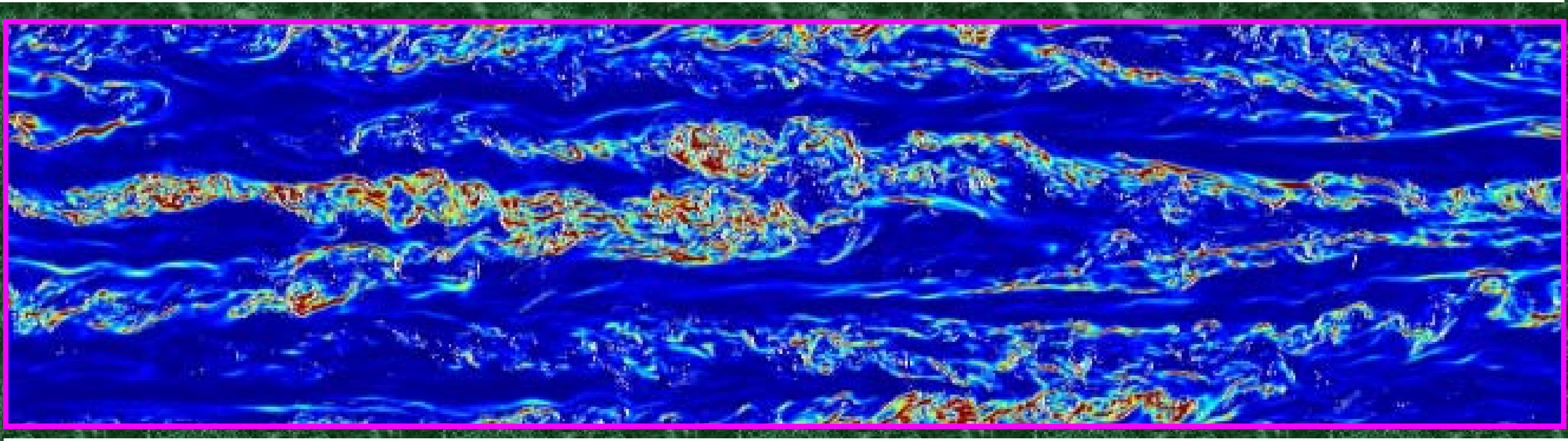
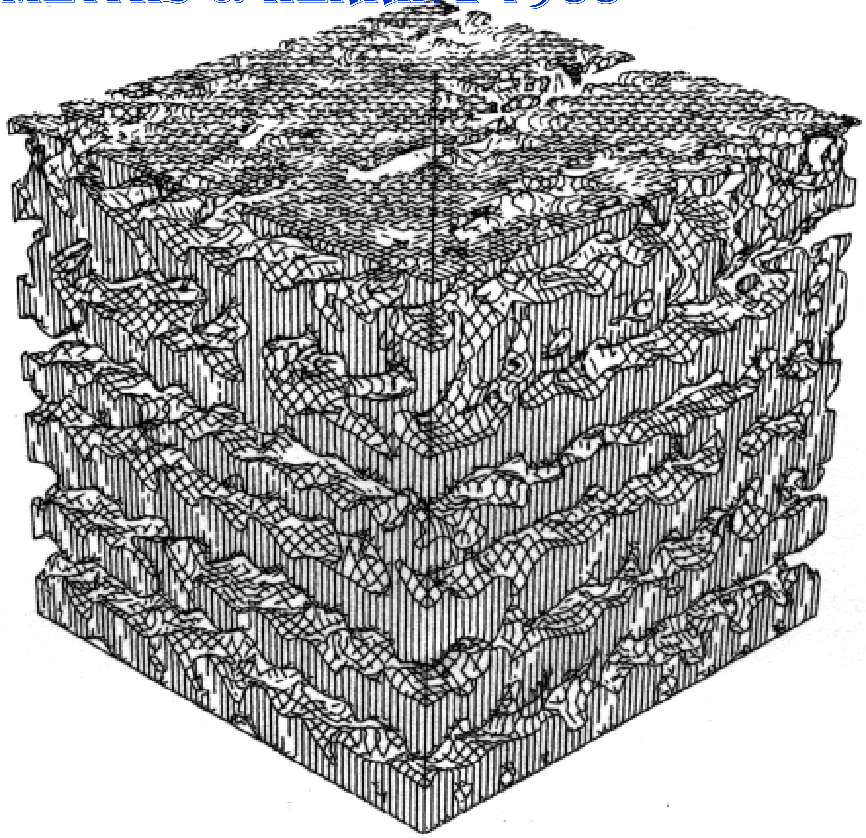


Figure 16: Snapshot of ε on a (x, z)-plane extracted from run D8. From low to high dissipation goes from dark blue, light blue to red.

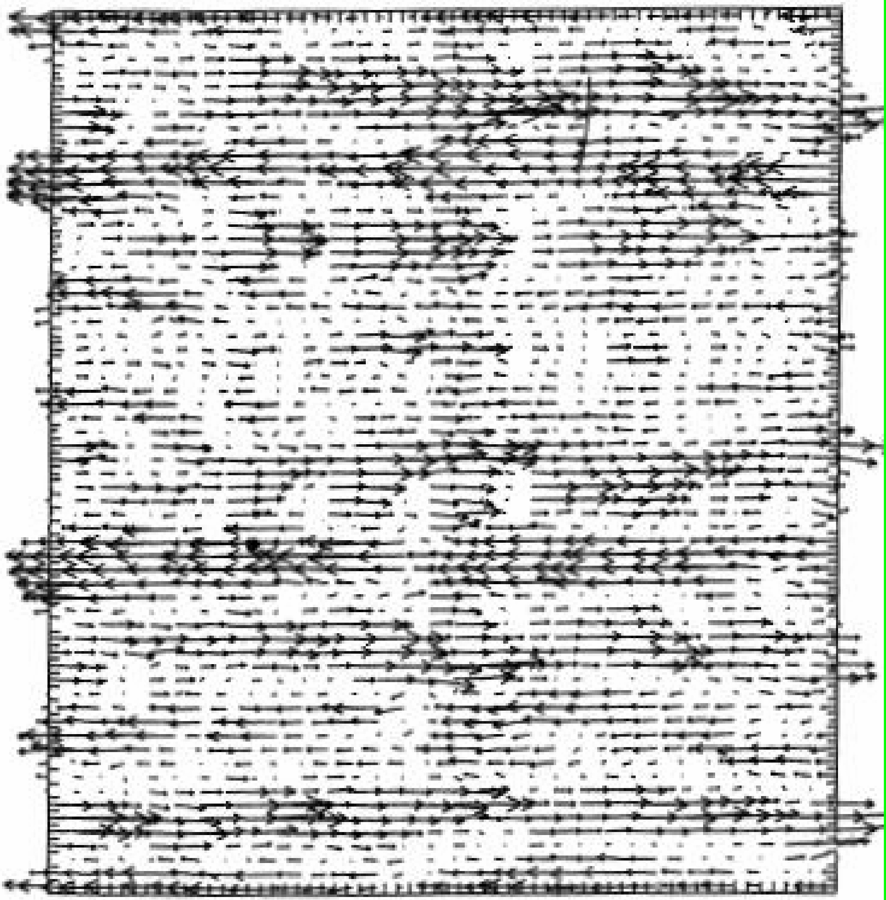
LAYERS IN STRONGLY STABLY STRATIFIED TURBULENT FLOWS

Numerical experiments in forced stably stratified turbulence

METAIS & HERRING 1988



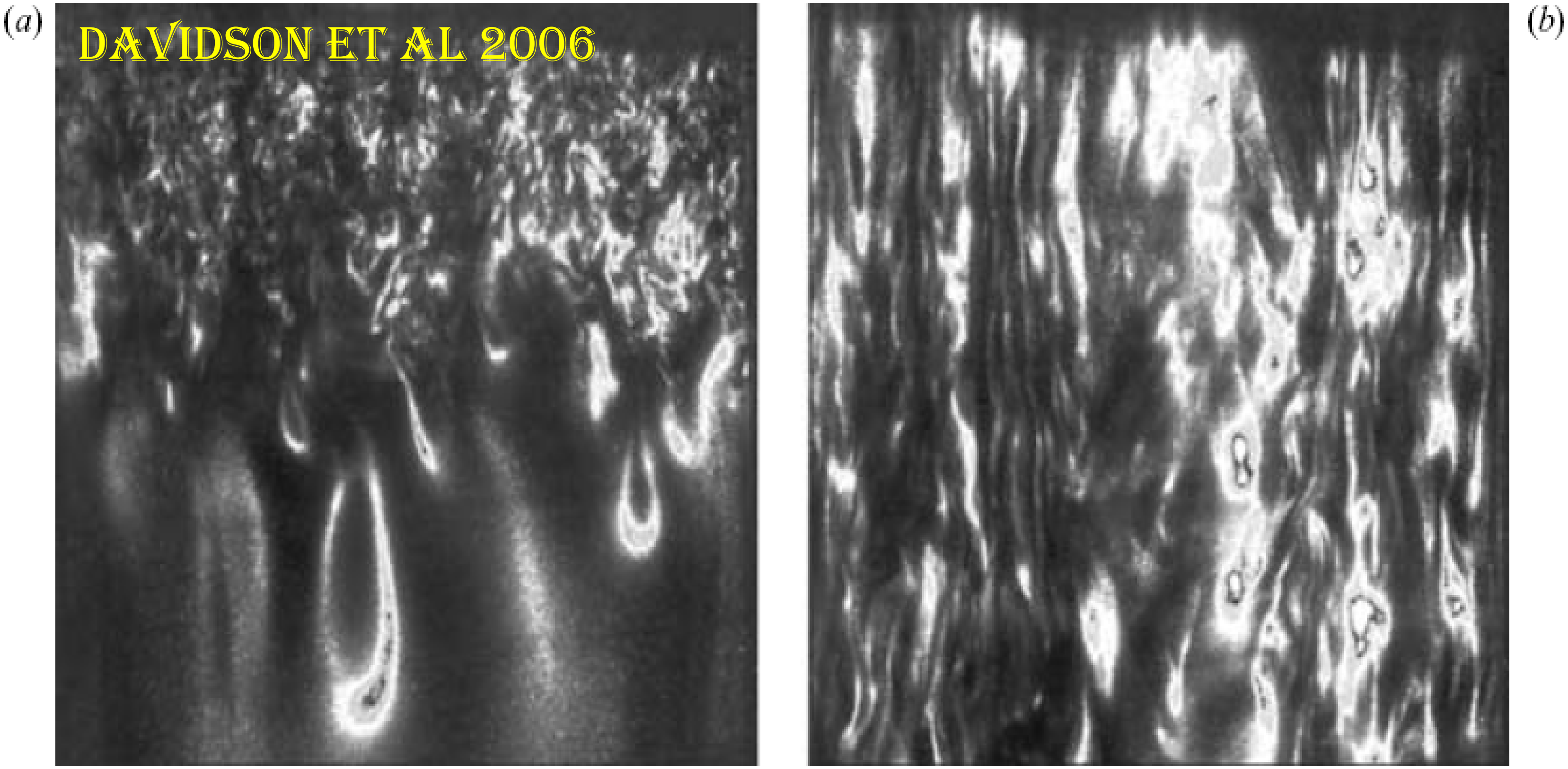
Isosurfaces of $u(x,y,z,t)$ (x-component of u)



Vector plots of $u(x,y,z,t)$ x,0,z

RAPIDLY ROTATING FRAME

On the evolution of eddies in a rapidly rotating system 143



DAVIDSON ET AL 2006

FIGURE 3. Images of the flow taken at different times after initiation of the turbulence. (*a*) $2\Omega t = 20$, (*b*) $2\Omega t = 60$. The mesh size was $M = 8\,\mathrm{cm}$ and the rotation rate $2\,\mathrm{rad\,s^{-1}}$. Note that columnar vortices are still evident at $2\Omega t = 60$. The images are 42 cm square.