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NAVAL UNDERSEA WARFARE CENTER DIVISION
NEWPORT, RHODE ISLAND

Technical Memorandum

**PROCEEDINGS OF THE
NUWC DIVISION NEWPORT SEMINAR SERIES ON
TURBULENCE AND ITS CONTROL**

1 October 1992

Compiled by:

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J. C. S. Meng

Weapons Technology and
Undersea Systems Dept.

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| 1. REPORT DATE 01 OCT 1992 | | 2. REPORT TYPE Technical Memorandum | | 3. DATES COVERED 01-06-1992 to 31-08-1992 | |
| 4. TITLE AND SUBTITLE Proceedings of the NUWC Division Newport Seminar Series on Turbulence and its Control | | | | 5a. CONTRACT NUMBER | |
| | | | | 5b. GRANT NUMBER | |
| | | | | 5c. PROGRAM ELEMENT NUMBER | |
| 6. AUTHOR(S) Promode Bandyopadhyay; J. Meng; A. Hussain; Steven Orszag; Daniel Nosenchuck | | | | 5d. PROJECT NUMBER | |
| | | | | 5e. TASK NUMBER | |
| | | | | 5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Undersea Warfare Center Division, Newport, RI, 02841 | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER TM 922089 | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) | |
| | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited | | | | | |
| 13. SUPPLEMENTARY NOTES NUWC2015 Additional authors: Brown, Garry; Roshko, Anatol | | | | | |
| 14. ABSTRACT This memorandum records the proceedings of a four-part seminar series on turbulence and its control sponsored by the Naval Undersea Warfare Center Division, Newport, RI, during the summer of 1992. The Naval Undersea Warfare Center Division, Newport, RI, organized a four-part seminar series titled Turbulence and Its Control during the summer of 1992. One seminar was held in June, one in July, and two in August. These seminars were an activity of NUWC's Hydrodynamics Sphere of Excellence, which is one of the Center's leadership areas. The presentation materials used during the seminars, consisting mostly of informal viewgraphs, are reproduced in this report in their original form. | | | | | |
| 15. SUBJECT TERMS Turbulence; Hydrodynamics Sphere of Excellence; viscous flow; RNG; renormalization group theory; magnetohydrodynamic method; bluff-body wakes | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT Same as Report (SAR) | 18. NUMBER OF PAGES 205 | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT unclassified | b. ABSTRACT unclassified | c. THIS PAGE unclassified | | | |

ABSTRACT

This memorandum records the proceedings of a four-part seminar series on turbulence and its control sponsored by the Naval Undersea Warfare Center Division, Newport, RI, during the summer of 1992.

ADMINISTRATIVE INFORMATION

This document was prepared by Code 8234 under internal funding.

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FOREWORD

The Naval Undersea Warfare Center Division, Newport, RI, organized a four-part seminar series titled *Turbulence and Its Control* during the summer of 1992. One seminar was held in June, one in July, and two in August. These seminars were an activity of NUWC's *Hydrodynamics Sphere of Excellence*, which is one of the Center's leadership areas. The presentation materials used during the seminars, consisting mostly of informal viewgraphs, are reproduced in this report in their original form.

In the first seminar, Professor Hussain discussed in great depth the viscous flow physics of the numerically simulated "simple" problem of the interaction between two vortices.

In the second seminar, Professor Orzweg presented renormalization group (RNG) theory, which has generated a great deal of interest recently due to its surprising success in the rational calculation of widely different turbulent flows. RNG theory has already been closely scrutinized by many independent groups. In high Reynolds number practical flows, particularly those with strong anisotropy, RNG might become the standard tool.

The third seminar, led by Professors Nosenchuck and Brown, focused on a novel magnetohydrodynamic method of turbulence control. Professor Nosenchuck, with his keen aptitude for application, and Professor Brown, with his deep insight, made a formidable team. The turbulence control they have achieved with minimal power has surpassed that obtained with polymers.

In the fourth and final seminar, Professor Roshko reviewed our understanding of the turbulence in bluff-body wakes -- a topic that has always been of prime interest to him. He discussed his recent works, emphasizing the end-effects in laboratory experiments and highlighting the lack of agreement between so-called two-dimensional measurements and computer simulations.

1. New Aspects of Vortex Dynamics and Hydrodynamic Turbulence

**A. K. M. F. Hussain
University of Houston**

NUWC Division Newport, R. I.

SEMINAR NOTICE

**NEW ASPECTS OF VORTEX DYNAMICS AND
HYDRODYNAMIC TURBULENCE**

A. K. M. F. Hussain

Cullen Distinguished Professor

University of Houston

We try to shed some light on coherent structures and turbulence phenomena through studies of the new aspects of vortex dynamics, and of coherent vortex interaction with fine scale turbulence. These studies are done by direct numerical simulation of the Navier-Stokes equations. First, we explore the vortex reconnection mechanism and its role in turbulence cascade and mixing. We come to realize that core dynamics is important in reconnection and, although ignored so far, is very important for vortex dynamics. We explain core dynamics first in the framework of traditional quantities as colliding wavepackets resulting from coupling of meridional flow and swirl, and then in the framework of a new mathematical tool - 'complex helical wave decomposition' - which gives a clearer understanding of the flow physics in terms of polarized vorticity waves, expressed in terms of the eigenmodes of the curl operator. Finally, we discuss the symbiotic relationship between coherent structures and incoherent turbulence and question the validity of 'local isotropy' - the centerpiece of Kolmogorov's equilibrium hypothesis and of virtually all theories of turbulence.

Wednesday, 3 June 1992

Conference Room, Bldg. 990 (6th Floor)

Time: 10:30 AM

POC: Dr. Promode R. Bandyopadhyay (Code 804; x2588)

1-3/1-4

Reverse Blank

UNDERSTANDING TURBULENCE VIA VORTEX DYNAMICS

Outline

0. Coherent structures \neq flow visualization.
1. Review Reconnection mechanism
2. Vortex core dynamics / polarized vorticity
3. Coherent structure / fine-scale turb. interaction
4. Viscous generation of helicity

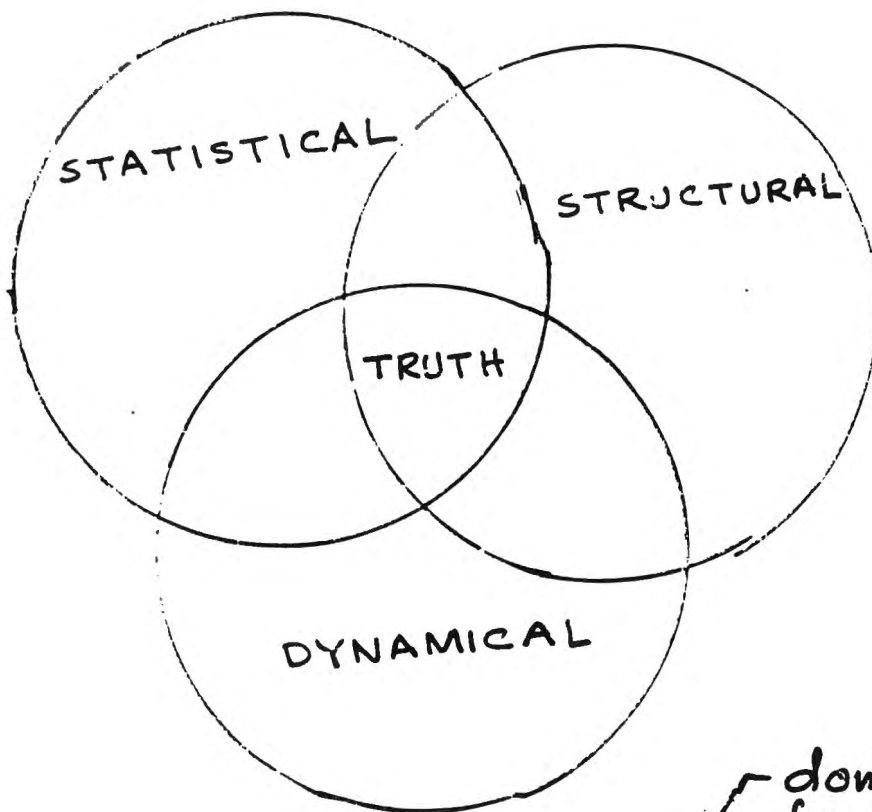
3 Approaches to turbulence

statistical (1940's →)

structural (1970's →)

Dynamical (1980's →)

will not review: mainly mention our ideas



our focus: so far: structural } dominant features
new: also dynamical } Establish
structure evolution → statistics } Connectio
Least understood: LS ↔ finescal

Coherent Structures (CS)

⇒ char. feature of Turb. Sh. Flow

TURB. MANAGEMENT (ie. enhance & suppress)

via control of: GENERATION
GROWTH
INTERACTION
DECAY } of CS

POTENTIAL BENEFITS:

FUNDAMENTAL

TECHNOLOGICAL

extensively
studied
No time

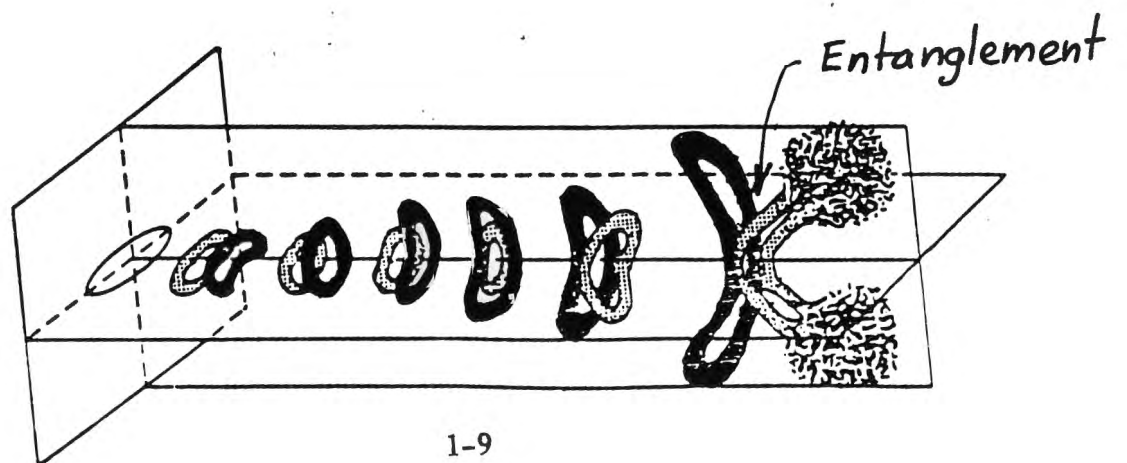
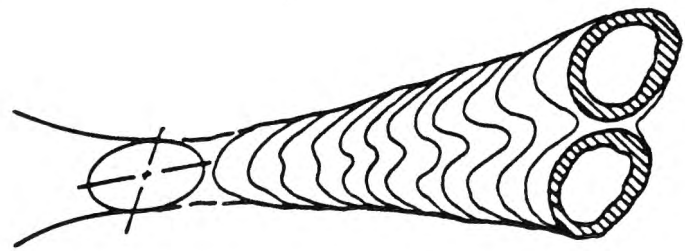
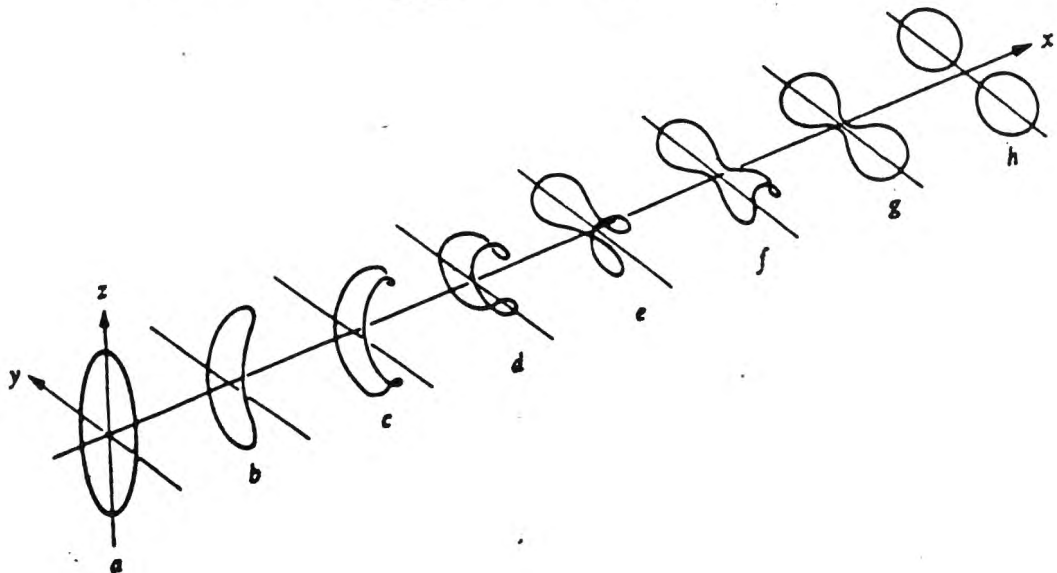
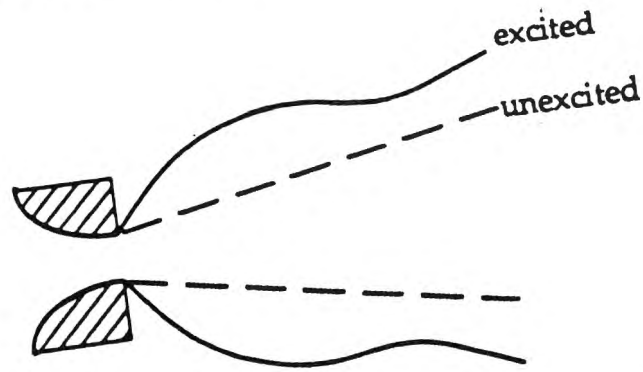
Topology \leftrightarrow Definition & Measurement
Roles in Turb. Phenomena (ent., mixing)
Dynamical Significance

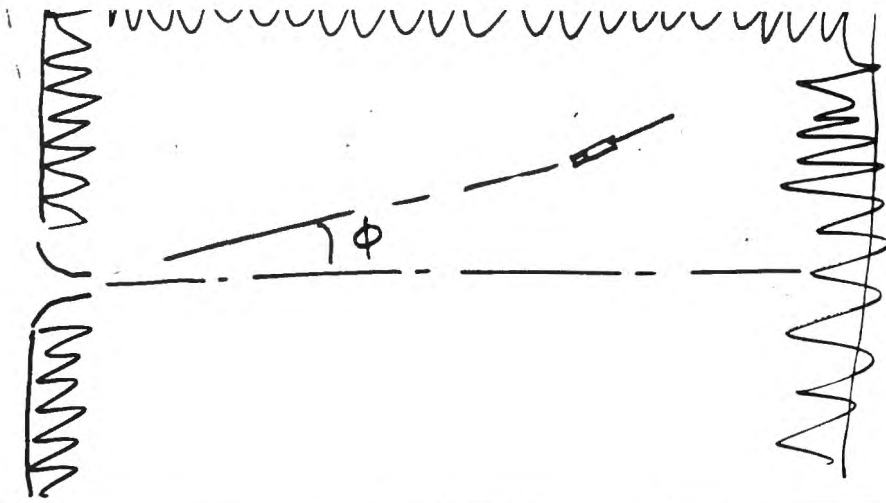
Management of turbulence phenomena?

→ Yes, by CS manipulation.

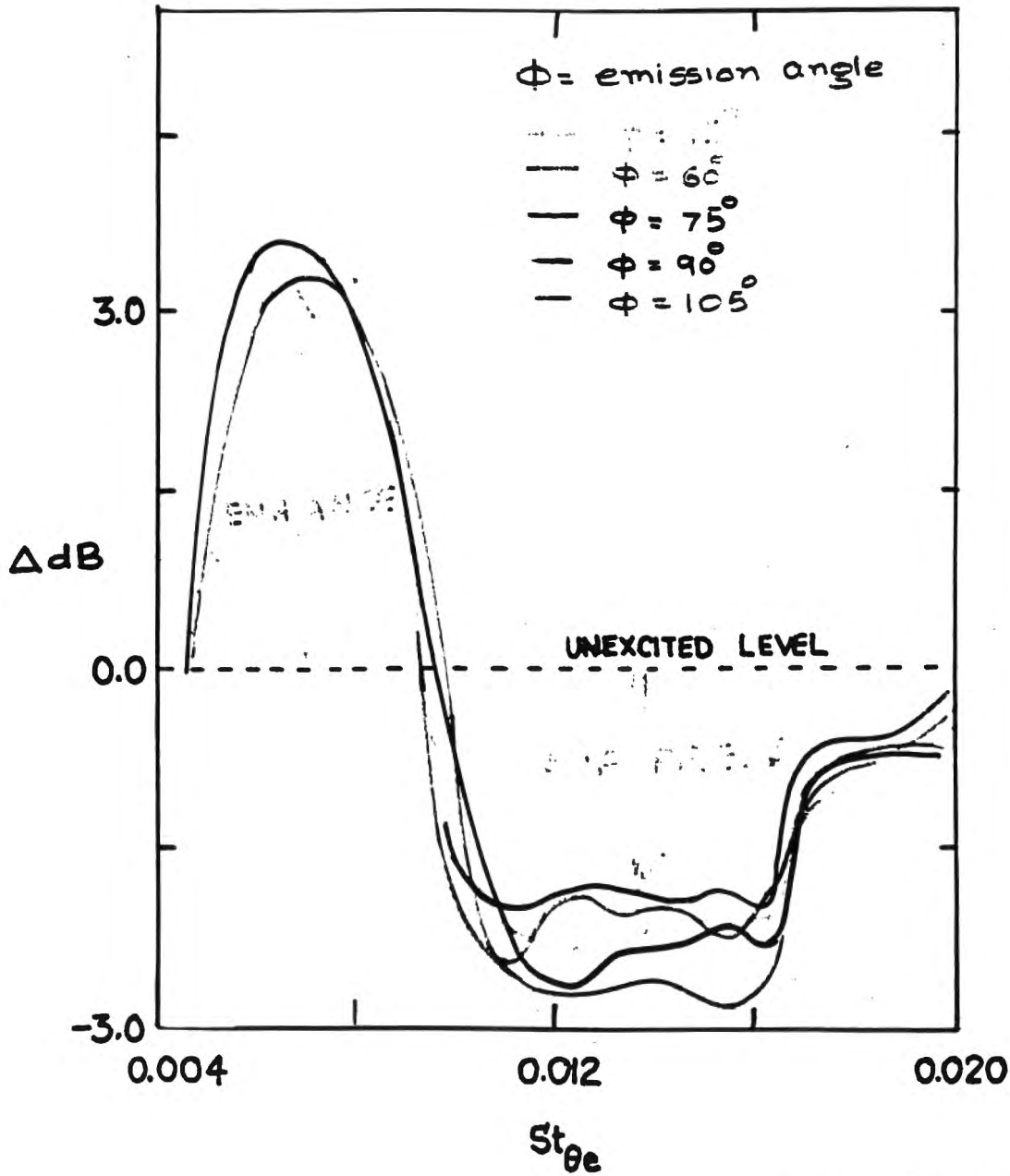
No CS, no control

Turb. control: elliptic jet





Hansen & H.
JFM (1974)



Aerodynamic noise suppression via excitation;
4 cm circular jet; $M = 0.15$

Mixing Layer

WHAT ARE CS?



Time-ave

ONR, DOE



roll-up

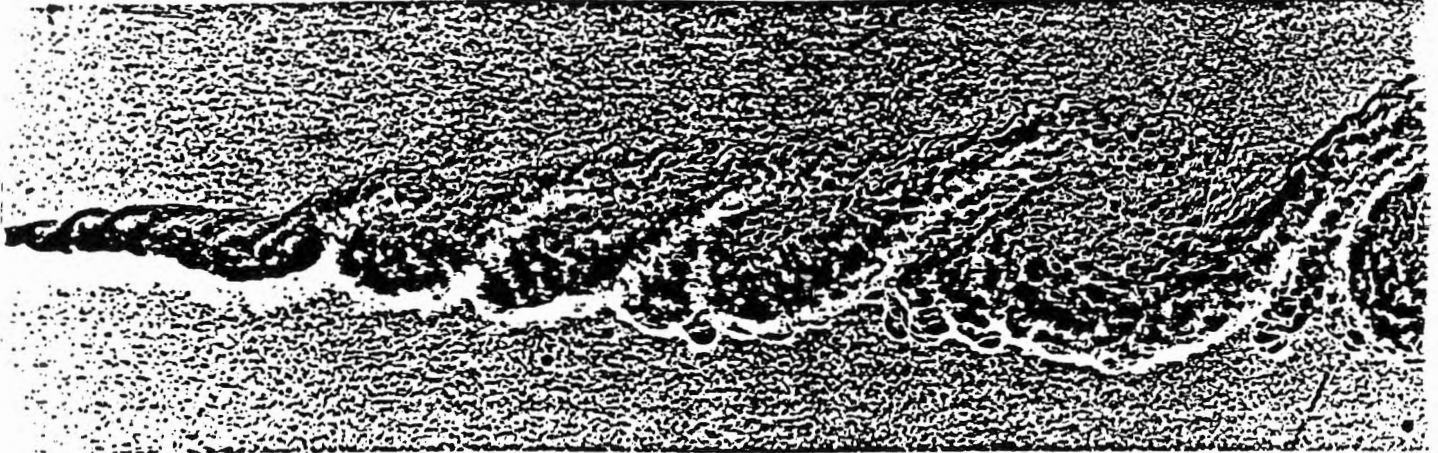
Paired

saddle

center

Instantaneous

streakline



Brown & Roshko, CalTech

Virtually all studies of CS

FLOW VISUALIZATION

Suffers from

Limitations

Mostly confusing (esp. in fully turb. flow)

Can be grossly misleading

Exceptions

Browand & Wiedman (ML)

Cantwell & Coles (Wakes)

Houston Studies

(CS, PJ, ES, ML, Wake, BL, CHF, HEP, Comb)

Recently Others

$$\frac{D\vec{\omega}}{Dt} = \vec{\omega} \cdot \nabla \vec{u} + \nu \nabla^2 \vec{\omega}$$

self-aug. (stretching)

$$\frac{Dc}{Dt} = \mathcal{D} \nabla^2 c$$

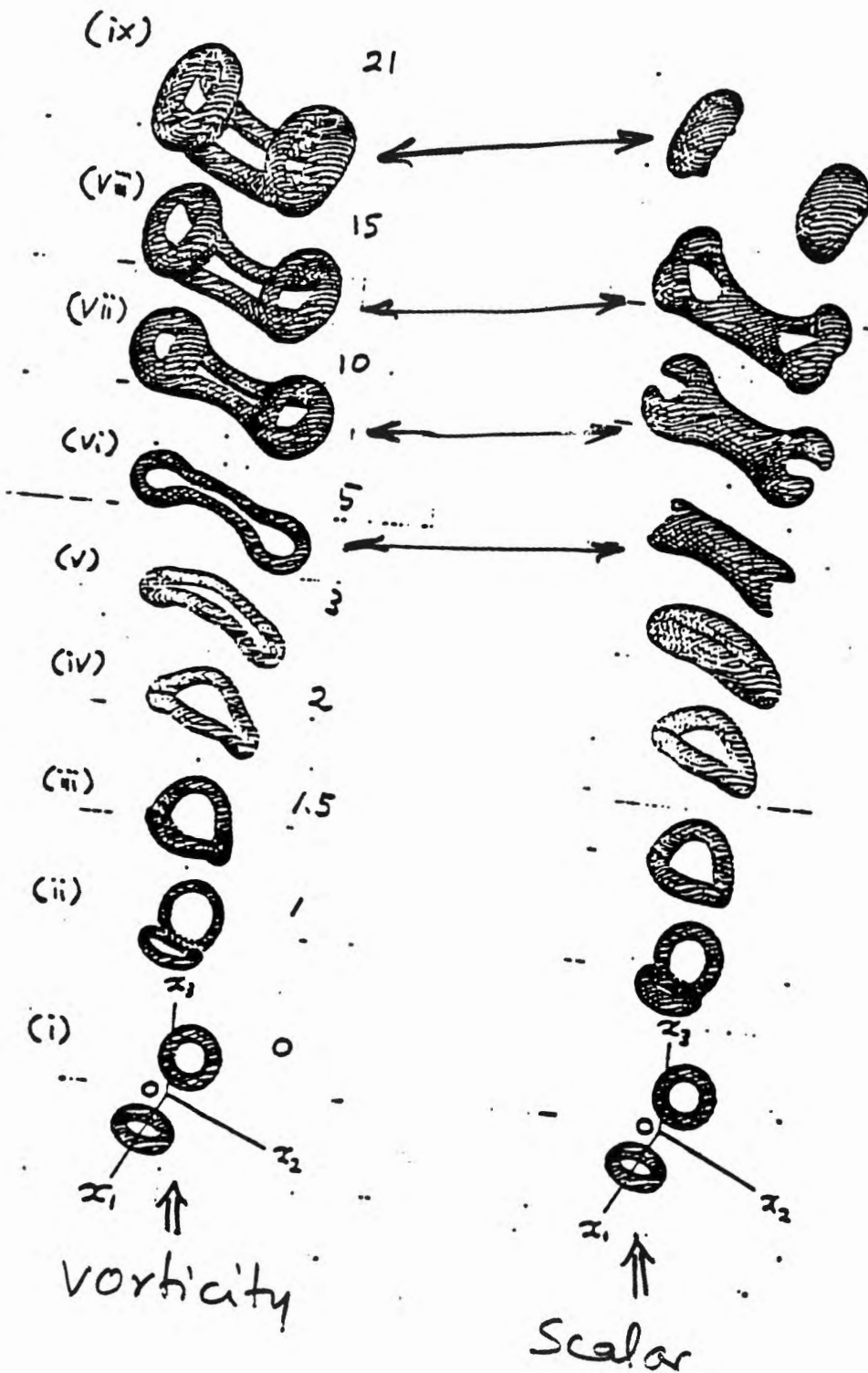
Boundaries of $|\vec{\omega}|$, c same in 2D if

$$Sc = \frac{U}{\nu} = 1$$

NOT SO in 3D even if $Sc \equiv 1$:

XAMPLE Cut & connect $|\vec{\omega}|$, c only

Two reconnections



$$C_2 = \Gamma / \gamma = 1000$$

Melandier &
Hussain (88)
Direct Sim.
NASA/Ames

Moffat, H.K. 1985 *J. Fluid Mech.* **159**, 359.

Schatzle, P.R. 1987, PhD thesis, California Institute of Technology.

Siggia, E.D. and Pumir, A. 1985 *Phys. Rev. Lett.* **55**, 1749.

Takaki, R. & Hussain, A.K.M.F. 1985, *Turbulent Shear Flows V*, Springer, 3.19.

Tsinober, A. & Levich, E. 1983 *Phys. Lett. A* **99**, 321.

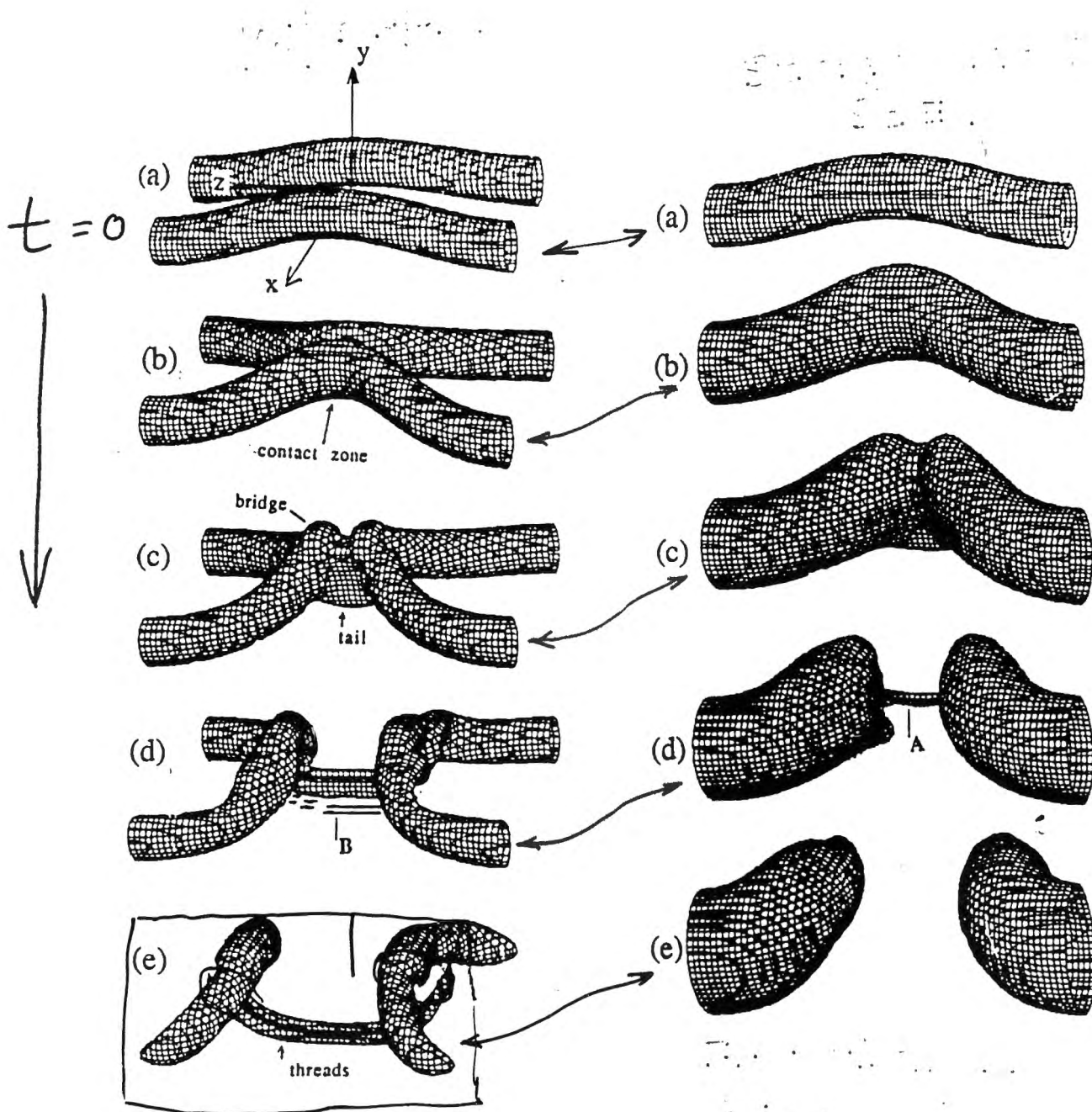


Figure 1. $|\omega|$ surface at 30% of the initial peak. (a) $t=0$;
(b) $t=2.25$; (c) $t=3.5$; (d) $t=4.75$; (e) $t=6.0$

Figure 2. Scalar at 5% of the initial peak. (a) $t=0$;
(b) $t=2.25$; (c) $t=3.5$; (d) $t=4.75$; (e) $t=6.0$

NOT REVIEW ALL TOPICS & RESULTS

What are CS?

Definition intensely debated for a decade

Hussain et al.
79, 81, 83, 86, 89

Repeat:

Flow domain with spatially periodic vorticity $\vec{\omega}(\vec{x}, t)$

Correlated part of $\vec{\omega} \leftarrow$ coherent vorticity
remainder \leftarrow incoherent turbulence

EDUCTIONI extracts CS in turb. flow

discusses: topology
coupling with incoh. turb.
dynamical significance

Defn. of vortex in a turbulent flow

$N_k \geq 1$ Kin. Vort. Ng.

$$N_k \equiv \left[\frac{\omega_k \omega_k}{2 s_{ij} s_{ij}} \right]^{1/2}$$

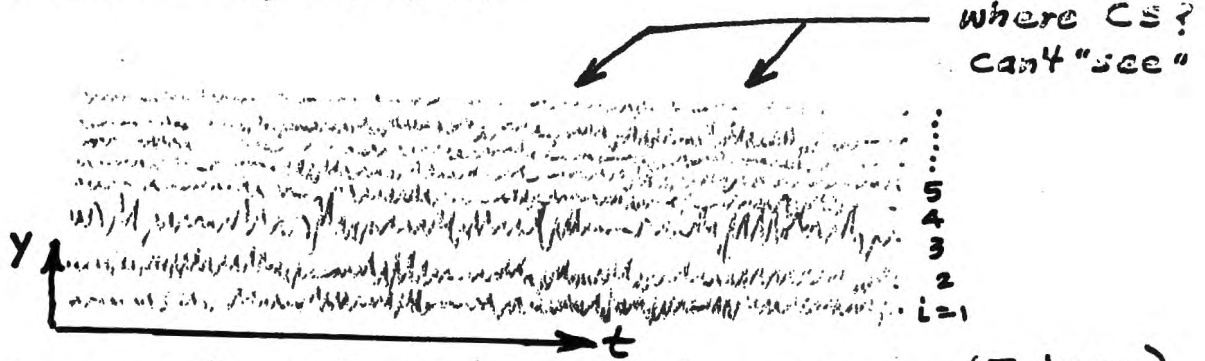
(Truesdell 5)

Also in Oceanic or atmospheric f

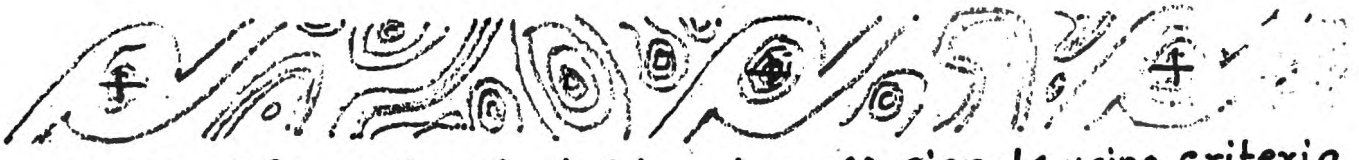
1. Place a trans. array of X-wires (or other sensors



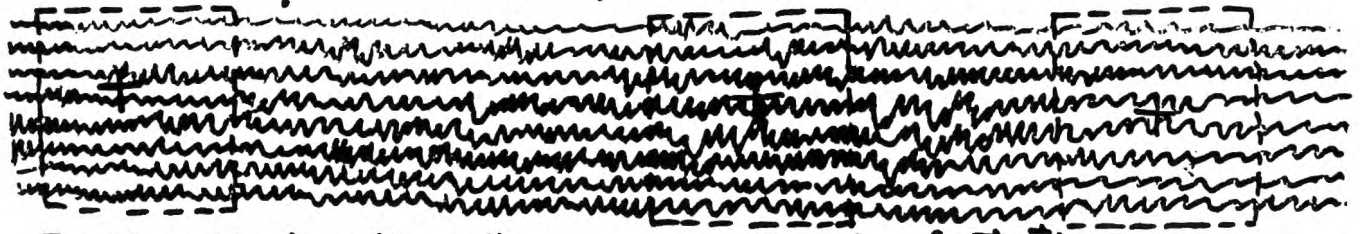
2. Obtain $u_i(t), v_i(t)$



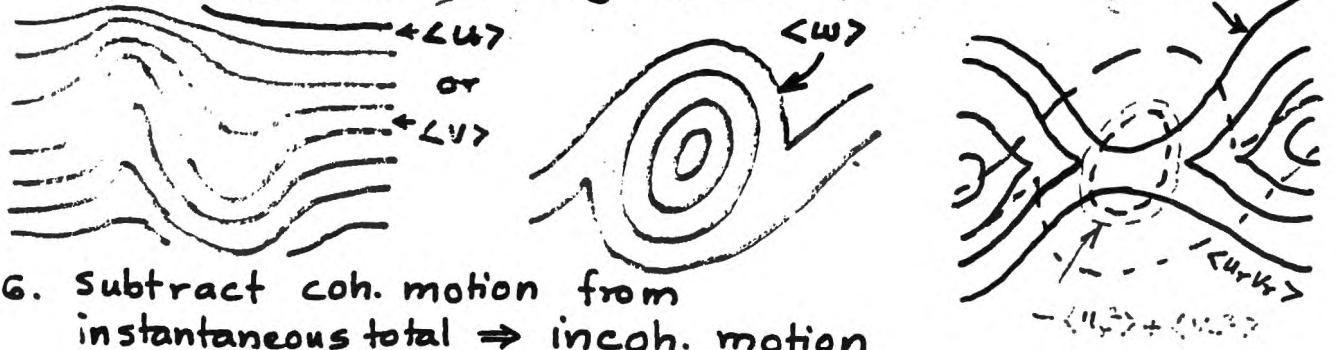
3. Smooth and obtain $w(x,y)$ $t \leftrightarrow x$ (T. hyp.)
DNS or image \leftarrow not nec.



4. Identify and collect (structures') signals using criteria



5. Iteratively align thru cross-correl. of $\bar{w}(\vec{x})$
then ensemble average \Rightarrow coh. motion



6. Subtract coh. motion from instantaneous total \Rightarrow incoh. motion
 $u - \langle u \rangle = u_r$

Applied to Num. Sim. also

Quantitative studies of CS

POD (Lumley/Sirovich)

Cond. Eddy (Adrian/Moin)

Our approach: vortex dynamics

(not well dev. for turb. environ.)

1. Defn. of a vortex in turb. flow

J. Jeong

2. Evolutionary dynamics in turb.

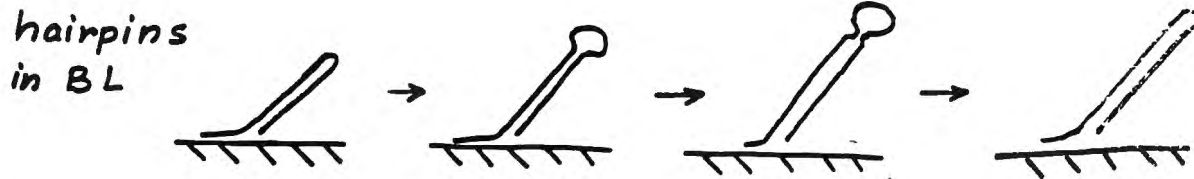
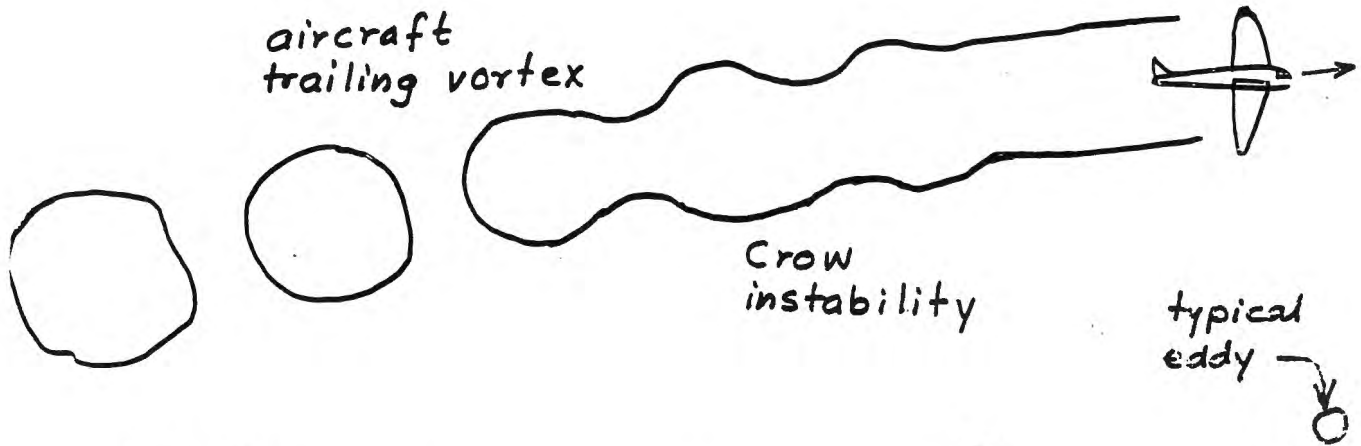
a. Vortex reconnection

b. Vortex/turbulence (fine-scale) interaction

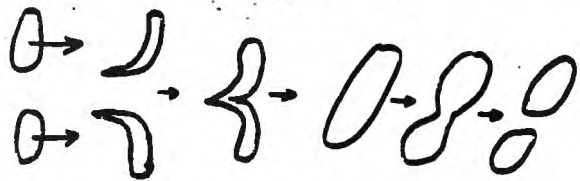
M. V. Melander

D. Visk

Some examples of reconnection



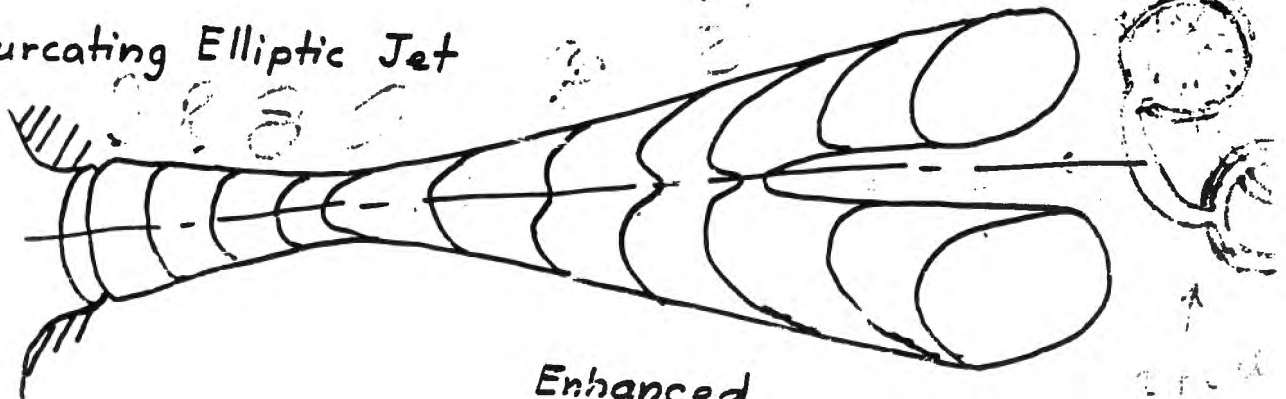
Two vortex rings (Kida et al.)



Elliptic ring breakup



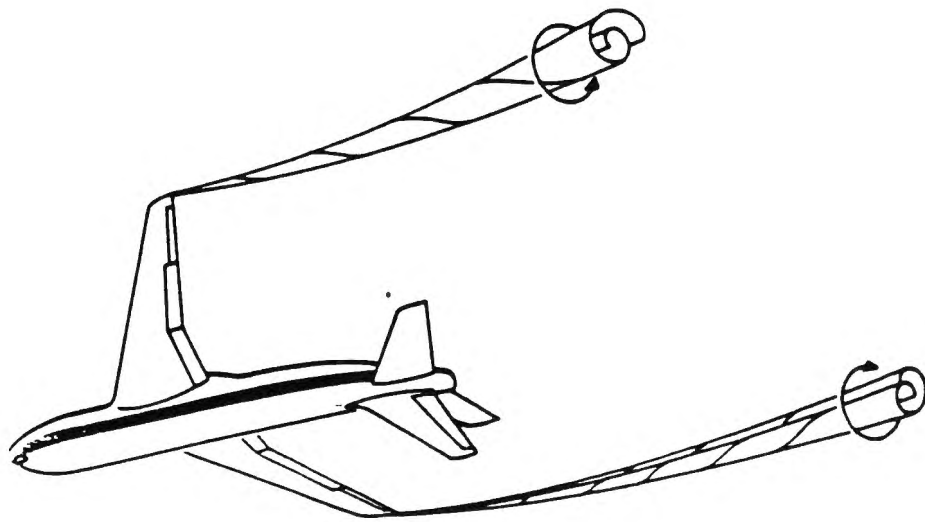
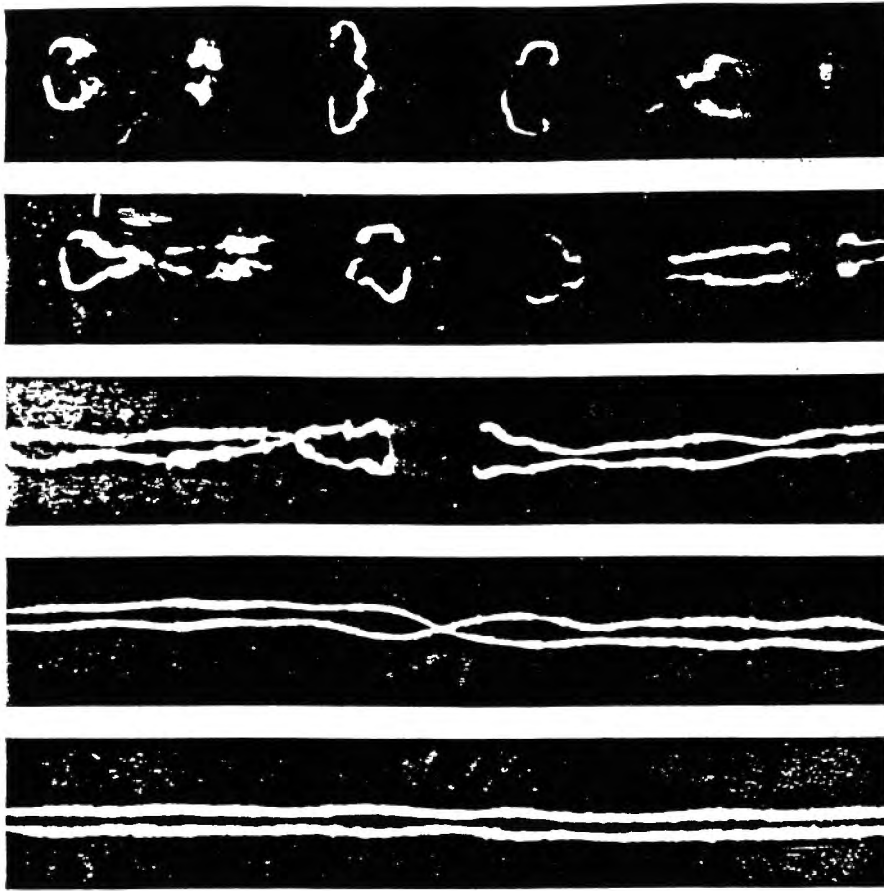
Bifurcating Elliptic Jet



Enhanced Mixing

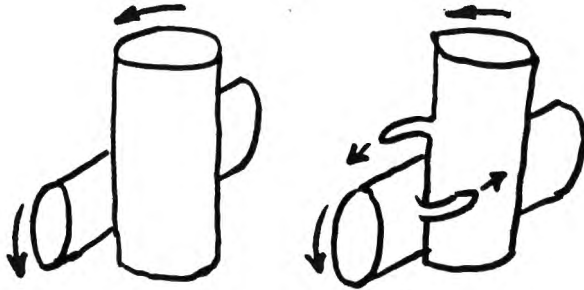
Also JFM (89)

HUSAIN & HUSSAIN (1983)
also in Liepmann & Narasimha (88)



Reconnection Mechanism

also Kida & Takaoka →



Melander & Zabusky (88)

Hairpins, entanglement

Viscosity unimportant

In our view: viscosity is crucial to initiate
but faster than viscous timescale

Reconnection: active research area e.g.

Siggia, Pumir, Kida, Zabusky, Saffman
Ashurst, Kerr, Meiron, Melander, Orszag,
Shelley, Aref

Timescale

σ : core size; Γ : circulation

Takaki & Hussain (85)

$$\sigma^2 / \Gamma = \frac{\sigma^2}{\nu} \cdot \frac{\nu}{\Gamma}$$

Schatzle (87)

$$\sigma / (s\nu)^{1/2}, \quad \sigma^2 / (\Gamma\nu)^{1/2}$$

Saffman & Leonard (87)

$$\frac{1}{2s} \log \frac{\sigma^2 s}{\nu}$$

Meiron et al. (88)

$$\frac{1}{2s} \log \Gamma / \nu$$

Melander & Zabusky (89)

$$\log \Gamma / \nu$$

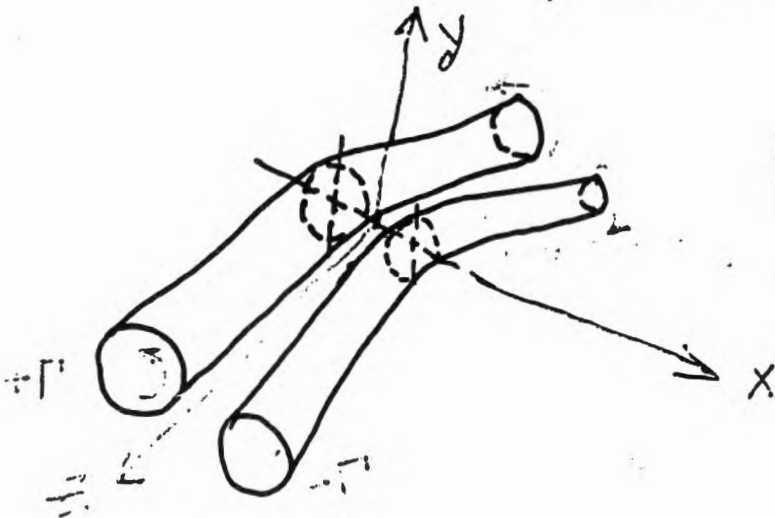


Turb. is
a tangle of
vortices

Reconnection occurs
continuously

Reconnection a
fundamental mech.
self-similarity: Universality

Siggia (1985)
showed filaments
become locally
anti-parallel



Melander & Hussain (88)

128^3 spectral, DNS

Compact function

initial δ^2

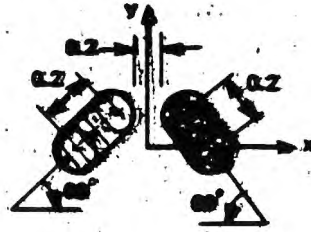
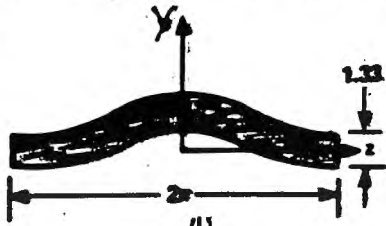
or δ^2

dealised

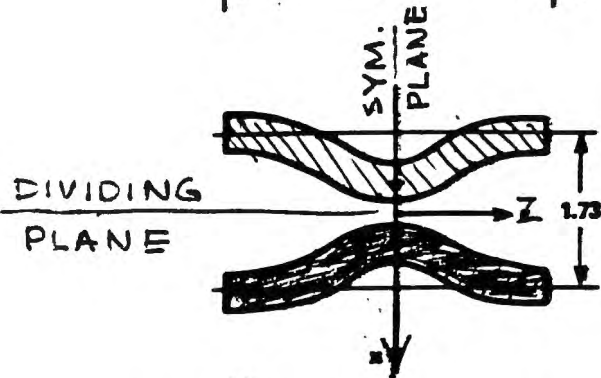
$\frac{1}{k}$ function

64³ Spectral, dealiased, $\frac{2}{3}$ truncation in k-space

$\Gamma/\nu = 1000$
 $Sc = 1$



Symmetric



Sinusoidal perturb.
 to induce collision

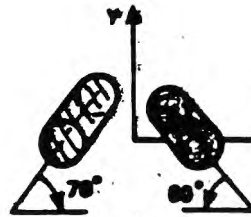
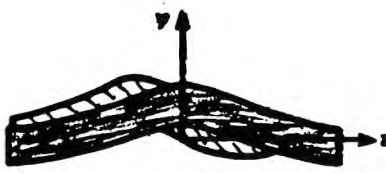
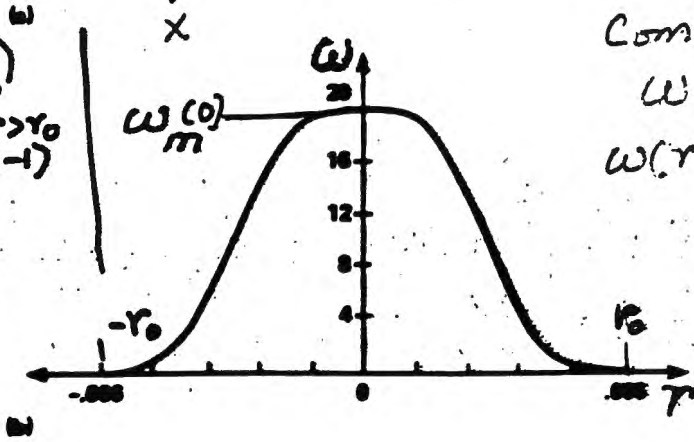
To localize crosslinking
 Initial vorticity is
 Compact Gaussian

$w(r) = 0 \quad r > 0.6$
 $w(r)$ readjusted to
 satisfy $\nabla \cdot \vec{w} = 0$

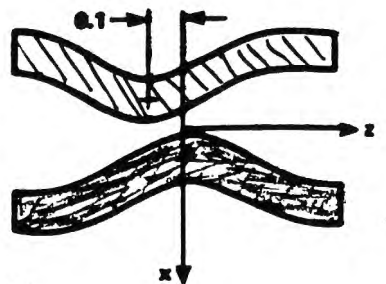
$$w(r) = 1 - f\left(\frac{r}{r_0}\right)$$

$$f(\eta) = e^{-\frac{K}{\eta}} e^{\frac{1}{\eta(\eta-1)}}$$

$$K = \frac{e^2}{2} \log 2$$

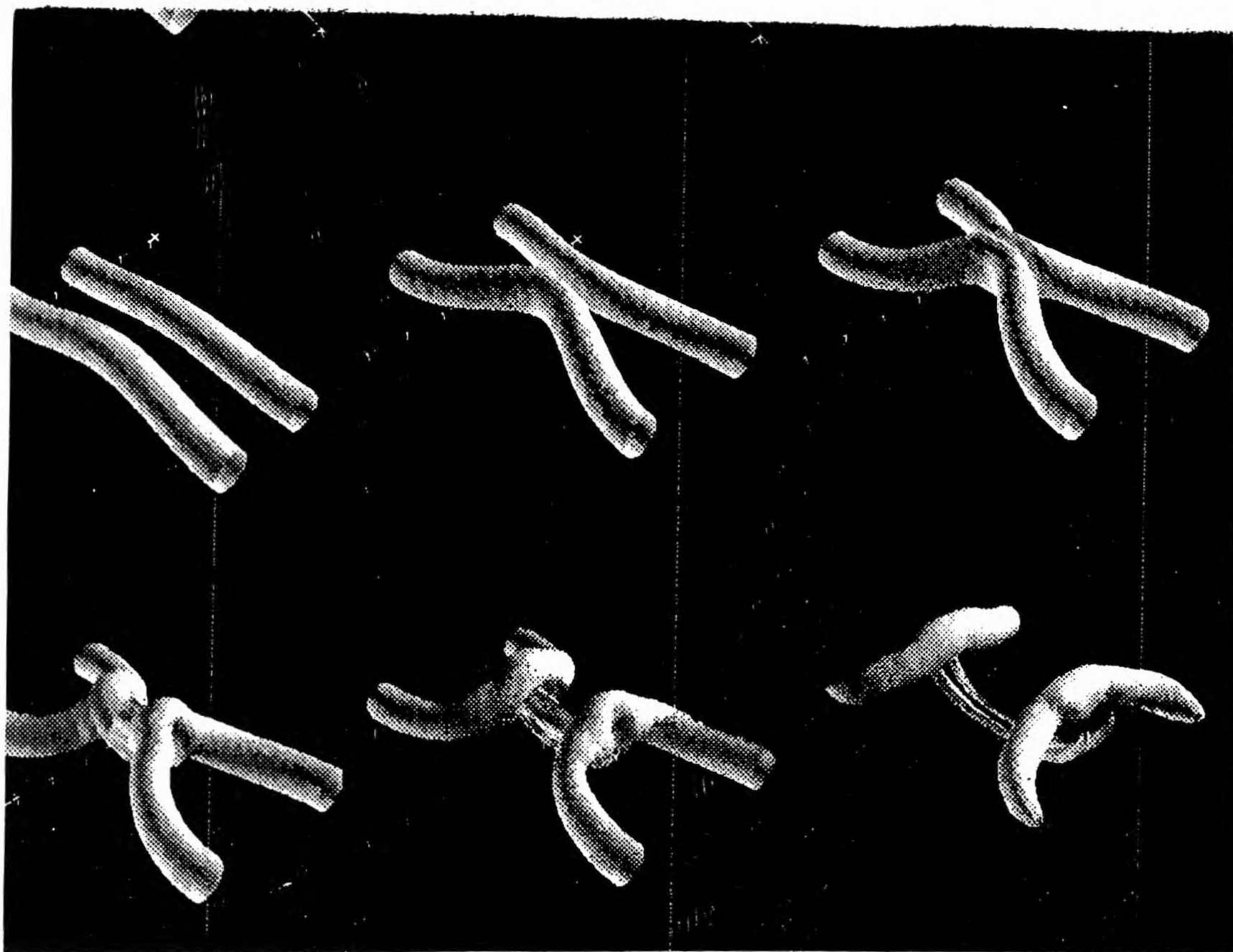


Asymmetric
 No explosive instab.
 Mention only
 diff.



Discuss results at
 n-d times $t \equiv \frac{t^*}{m} w_m(0)$
 $t = 0, 2, 3, 3.75,$
 4.5 and 6

1-25



t =
0
2
3

3.75
4.5
6

1 1. $t = t^*(A) : h_0 @ 0, 2, 3, 3.75, 4.5, 6; \frac{\Gamma}{\tau} = 1000$

'Bridging' Mechanism

→ the heart of reconnection

$\tau = 3.25$

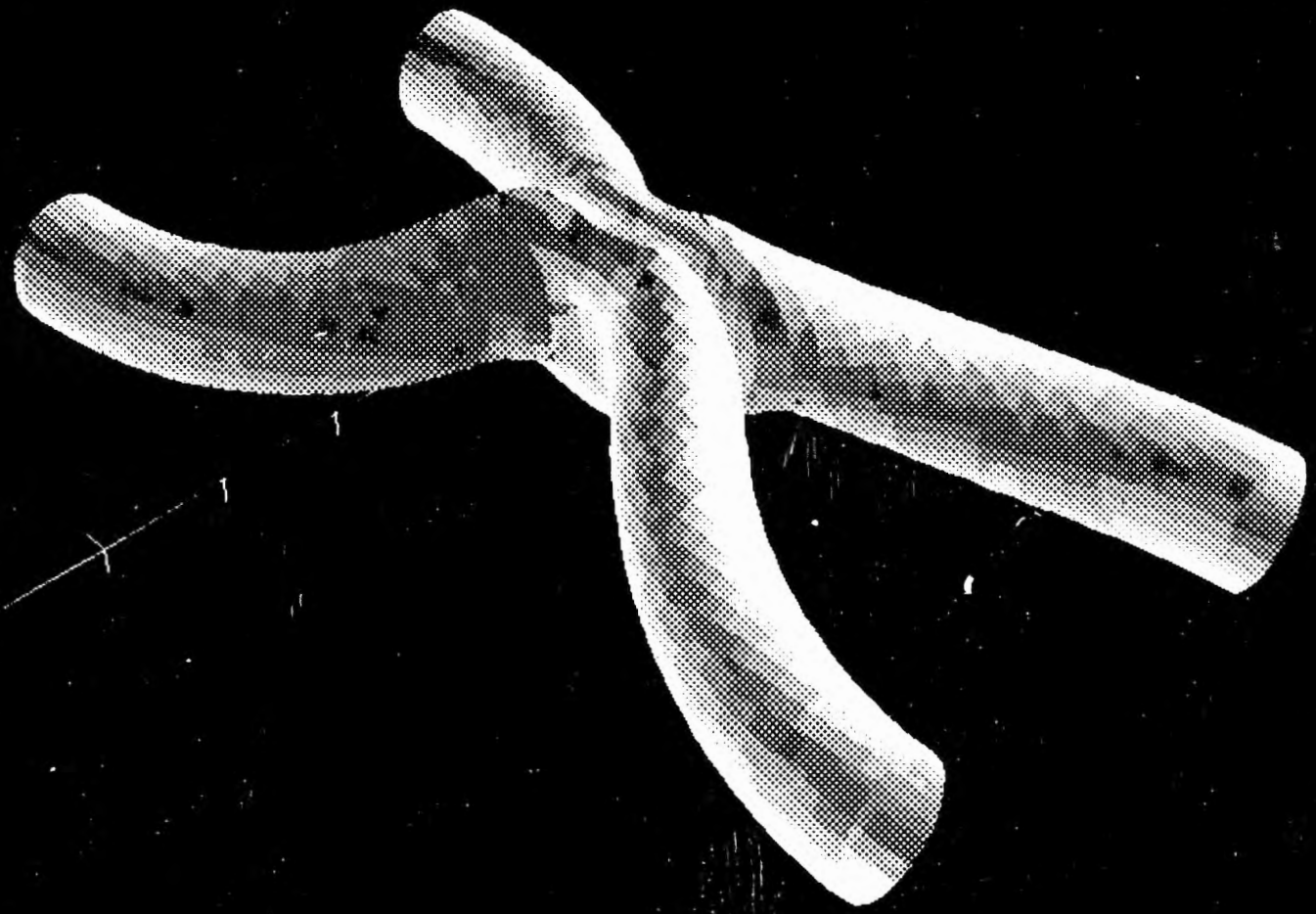
omega norm

Symmetric Reconnection Process

Re=1000, Sc=1, time=3.25, file=DXXI10.

CONTOUR LEVELS
6.00000

0.00x10++0 Nu
0.00x10++0 Utau
0.00x10++0 Re
0.00x10++0 Time
64x64x64 GRID



1-28

$t=3.75$

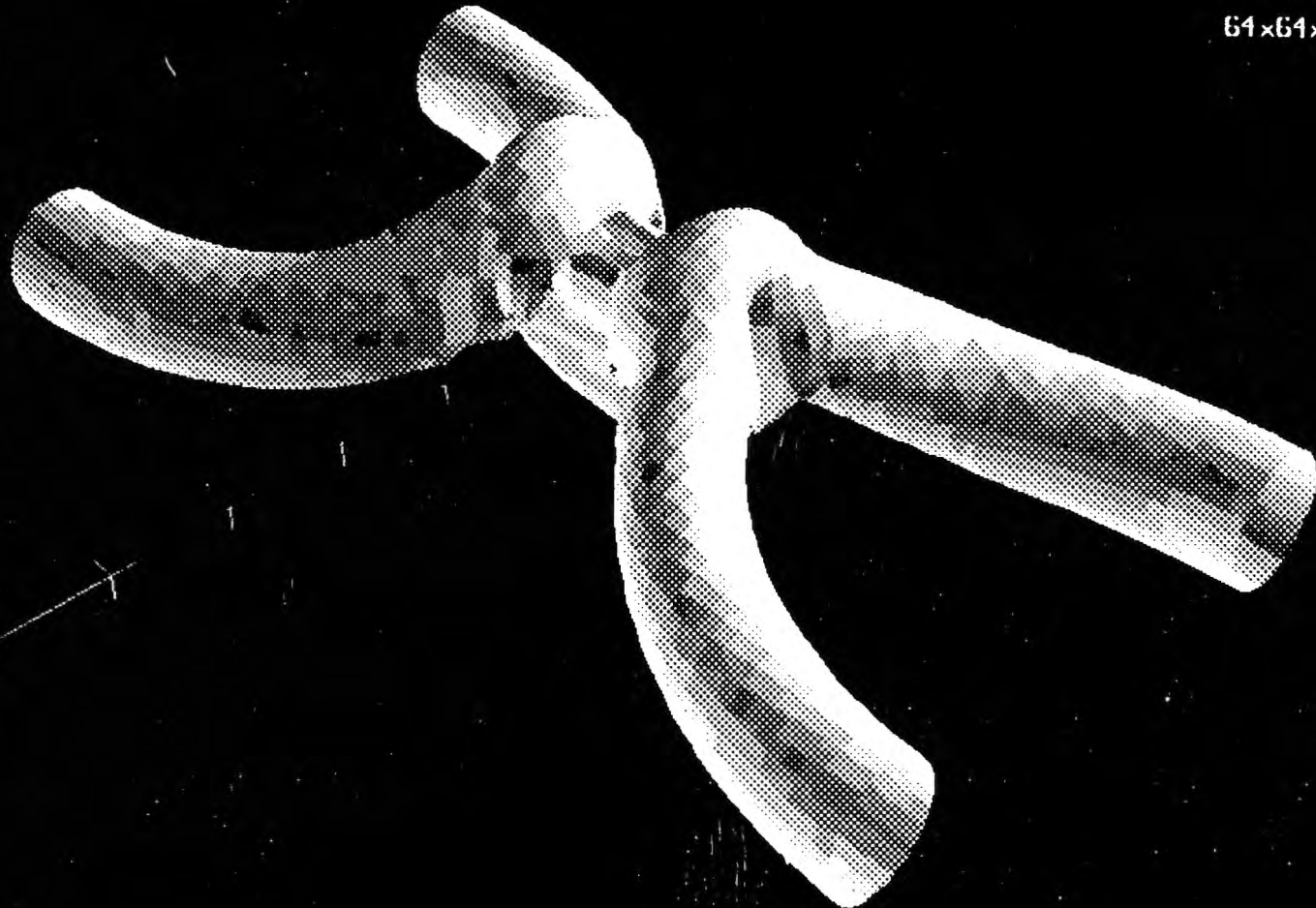
omega norm

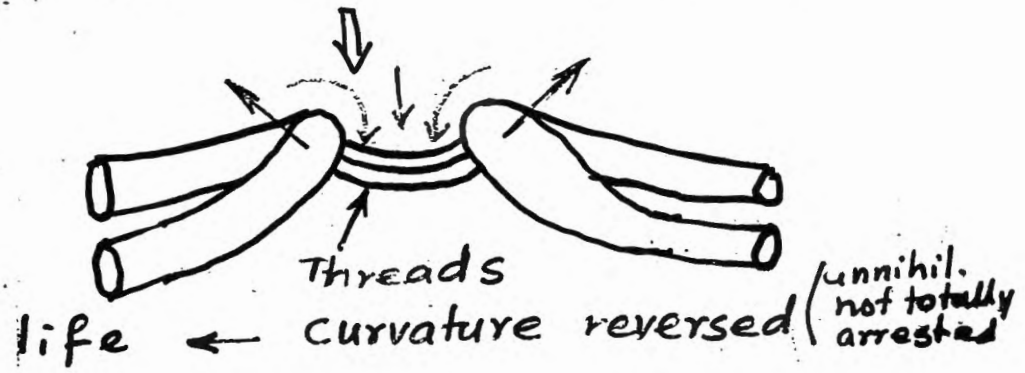
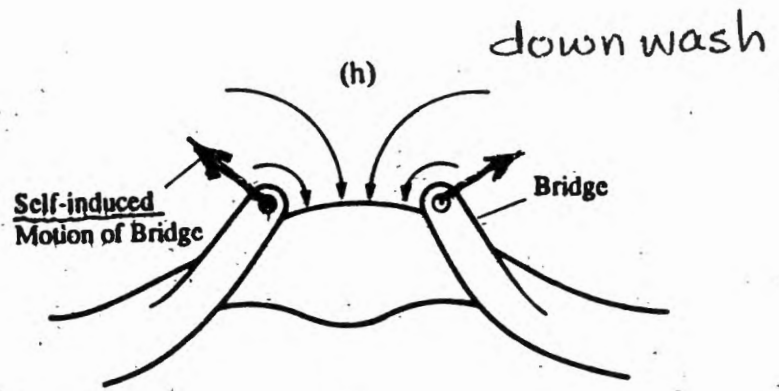
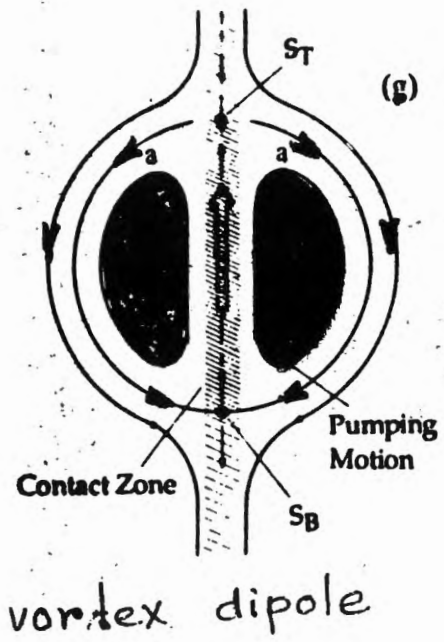
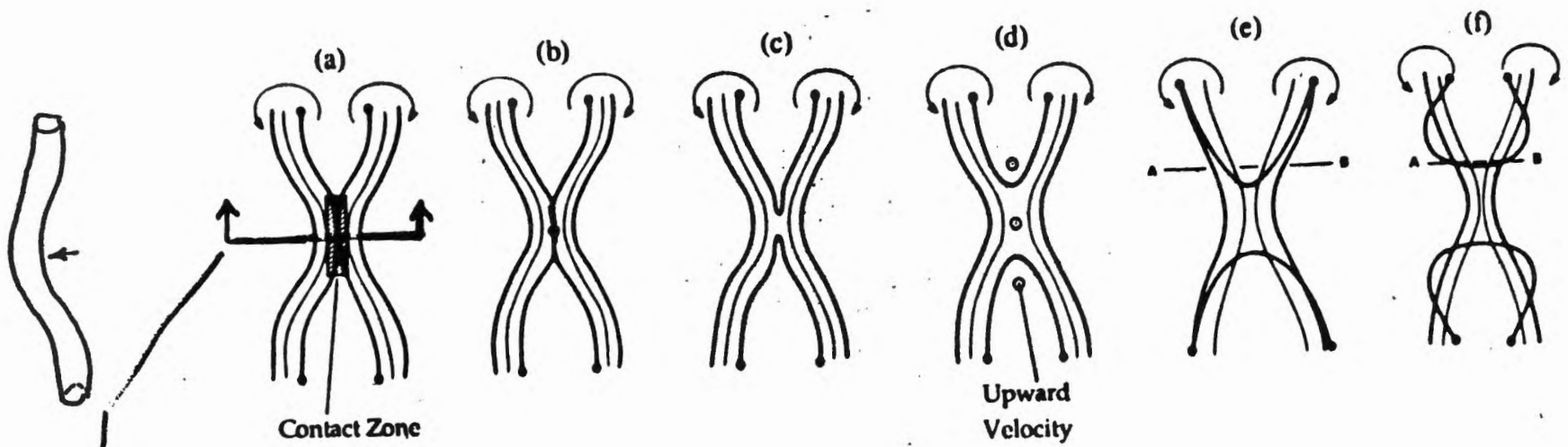
Symmetric Reconnection Process

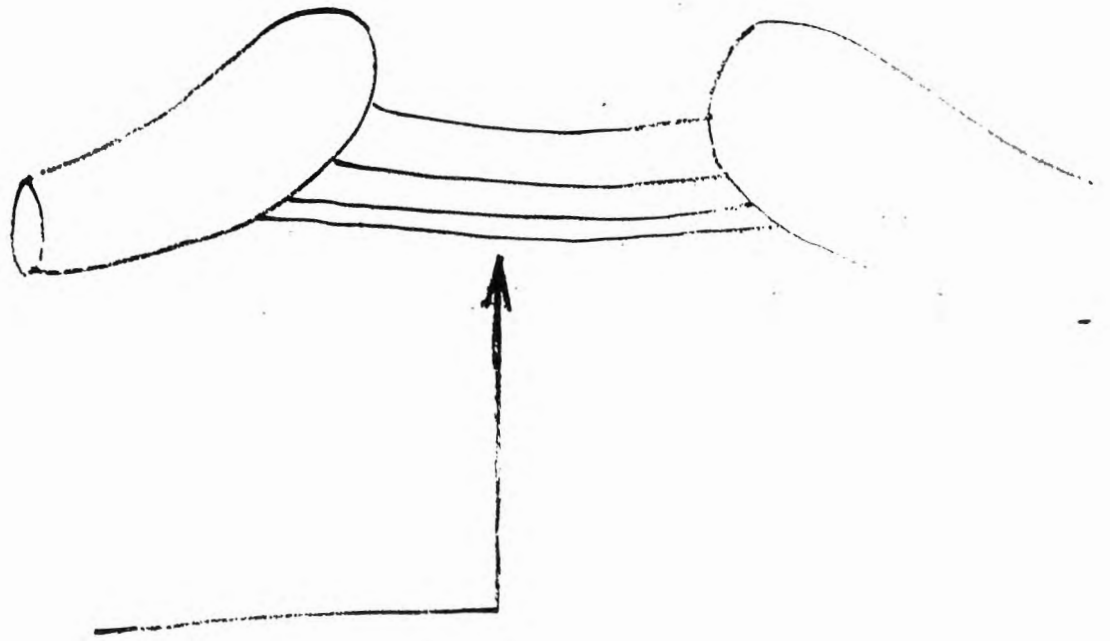
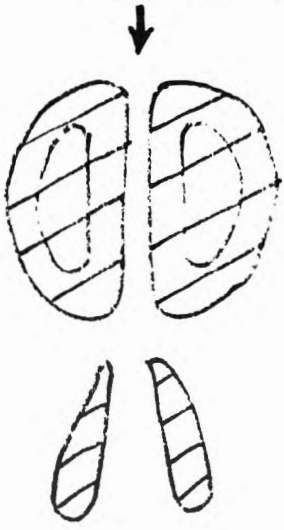
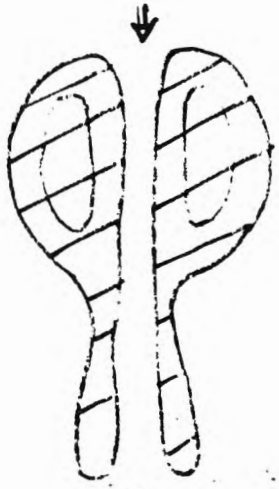
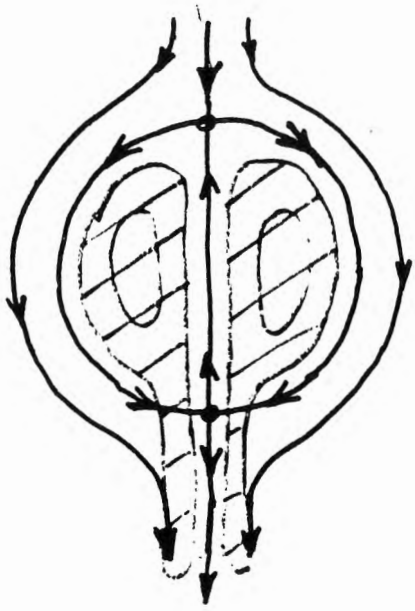
Re=1000, Sc=1, time=3.75, file=DXXT10.

CONTOUR LEVELS
6.00000

| | |
|------------|------|
| 0.00x10++0 | Nu |
| 0.00x10++0 | Utau |
| 0.00x10++0 | Re |
| 0.00x10++0 | Time |
| 64x64x64 | GRID |





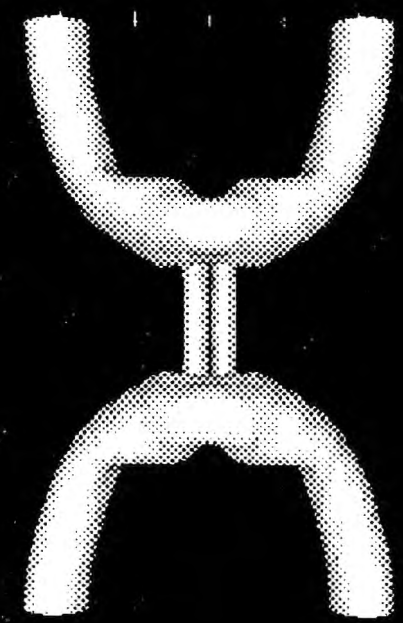
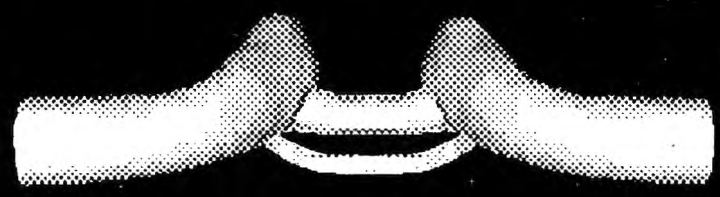
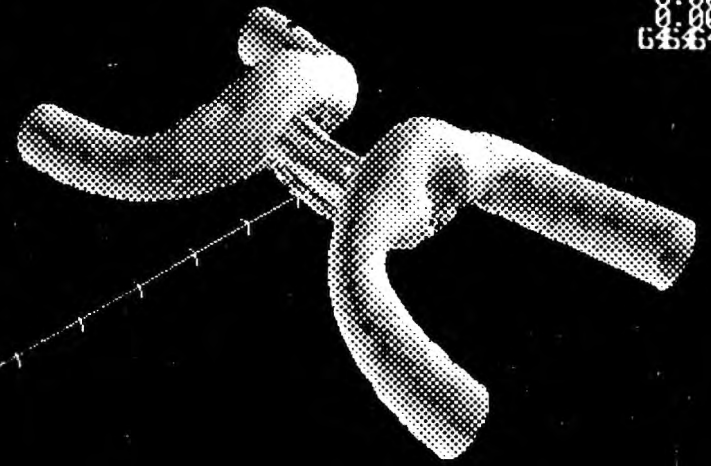


$t=4.5$

omega norm
Symmetric Reconnection Process
Re=1000, Sc=1, time=4.50, file=DXXT10.

CONTOUR LEVELS
5.00000

0.00x10+0
0.00x10+0
0.00x10+0
0.00x10+0
64x64 GRID



1-32

New Cascade mechanisms (also mixing)

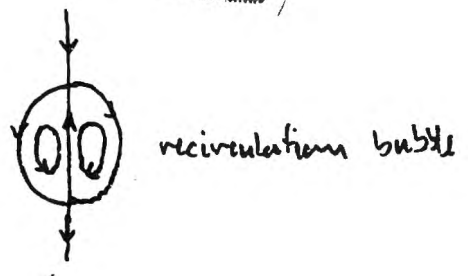
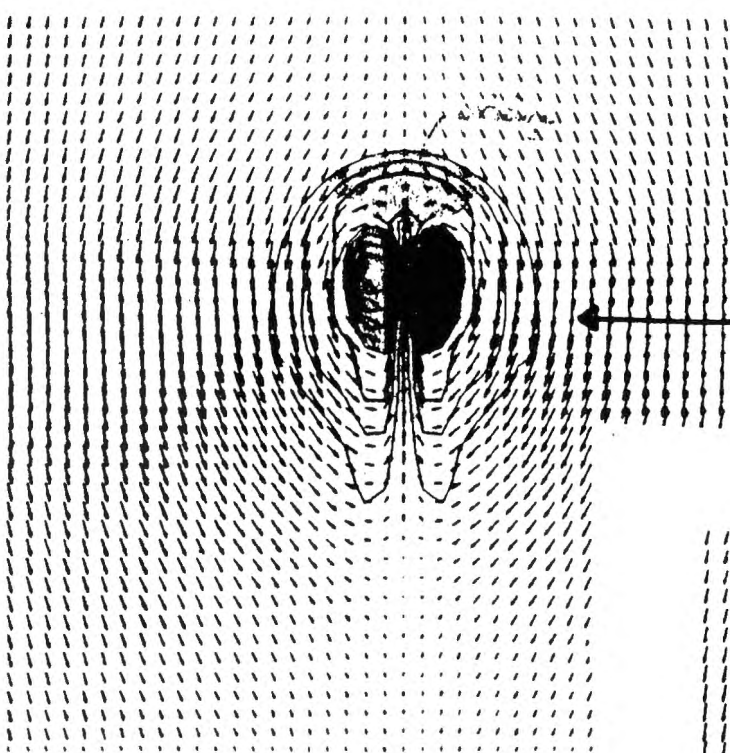
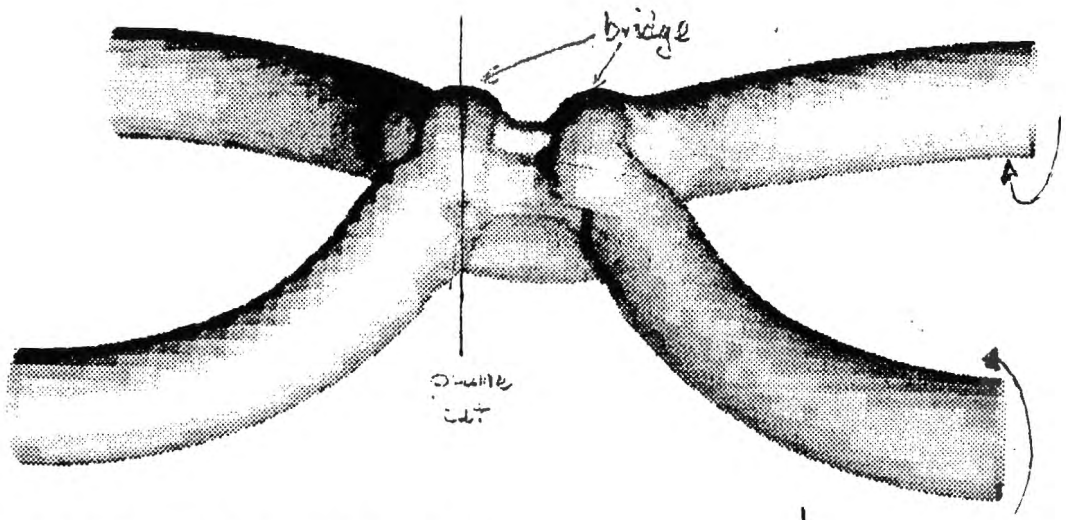
1. Threading
2. Head-tail formation
3. Separation of head from tail
4. Successive reconnection

(in addition to tearing & filamentation)

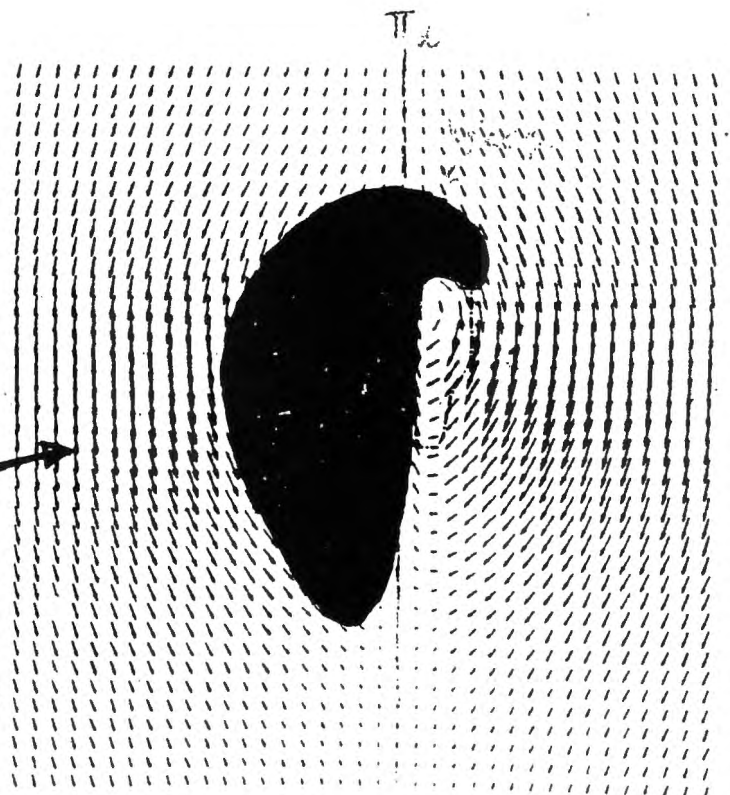
Threading unavoidable because

⇒ curvature reversal by "downwash"
overpowering weakened dipole,
more weakened by head-tail
formation and separation

$t = 3.5$ | $T_s \approx T_d$ half way through the reconnection



vorticity magnitude

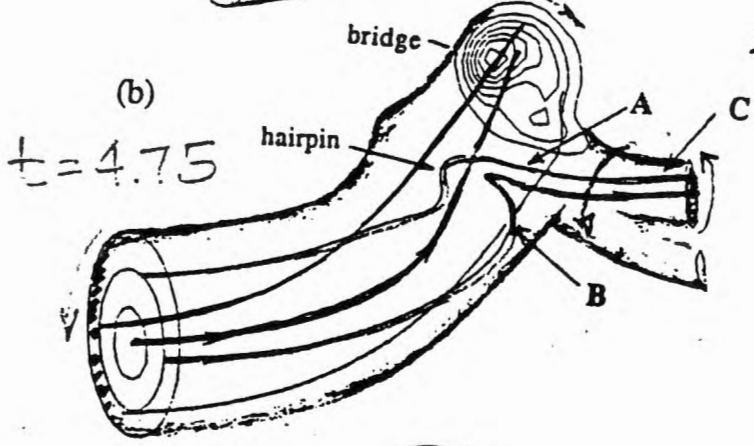
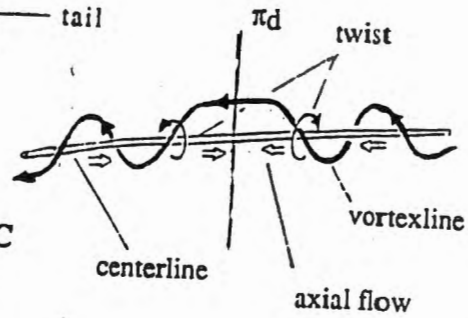
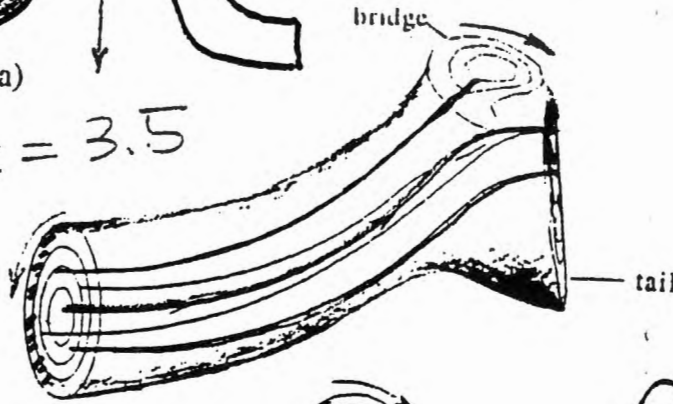


passive scalar



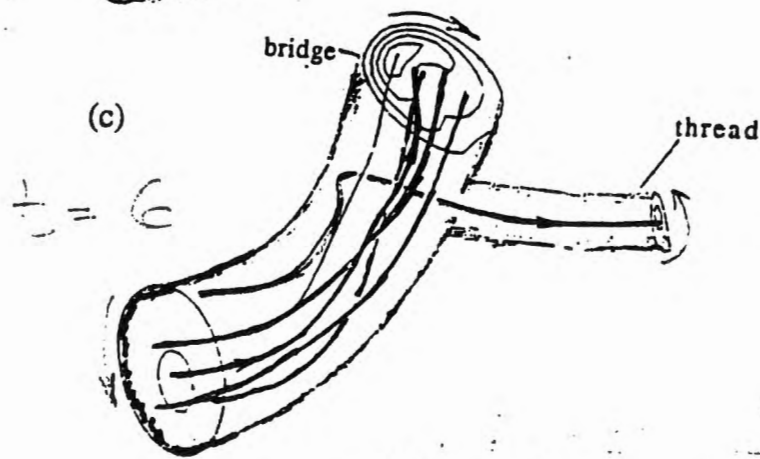
(a) $t = 3.5$

- P_w to lower
(d) w_{max} in bridge

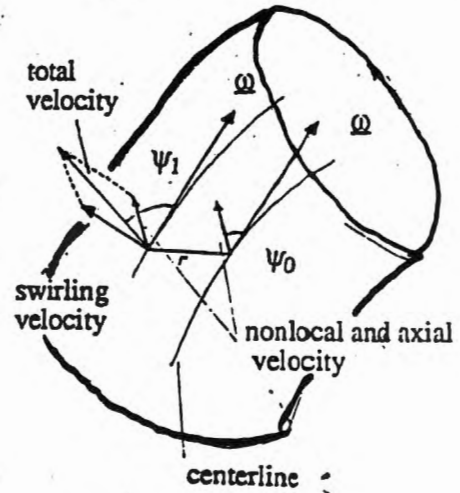


(b) $t = 4.75$

(e) min. h_r in bridge core



(c) $t = 6$



Skewed w distrib. in bridge

Twist \leftarrow pumps fluid to πd

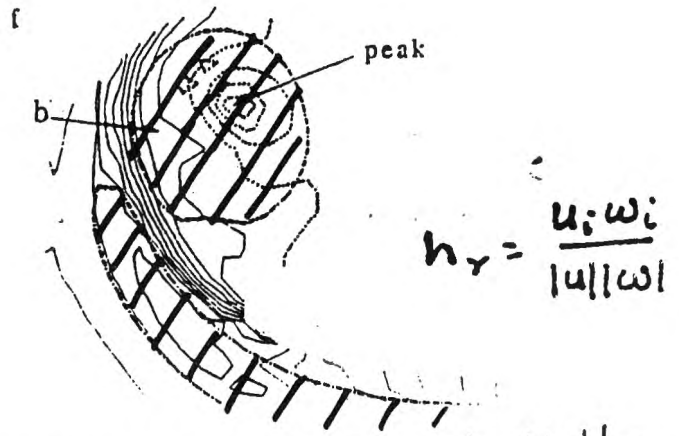
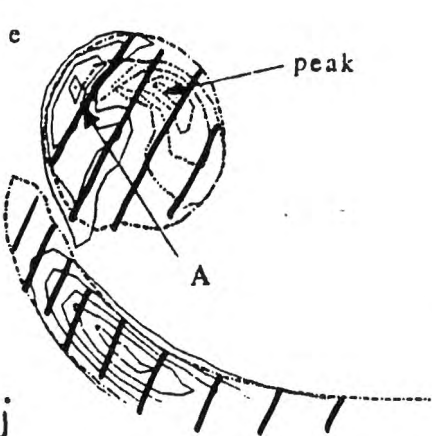
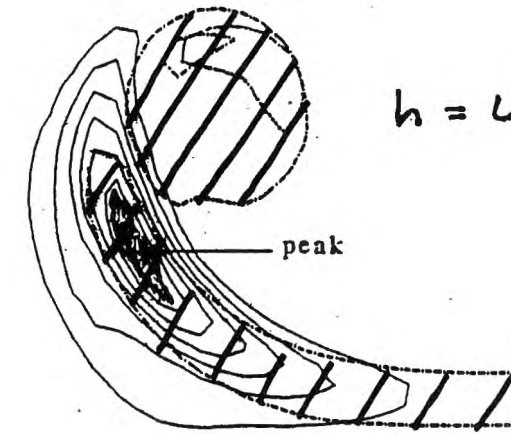
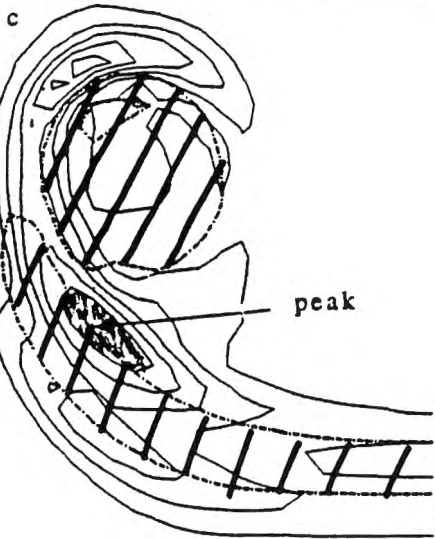
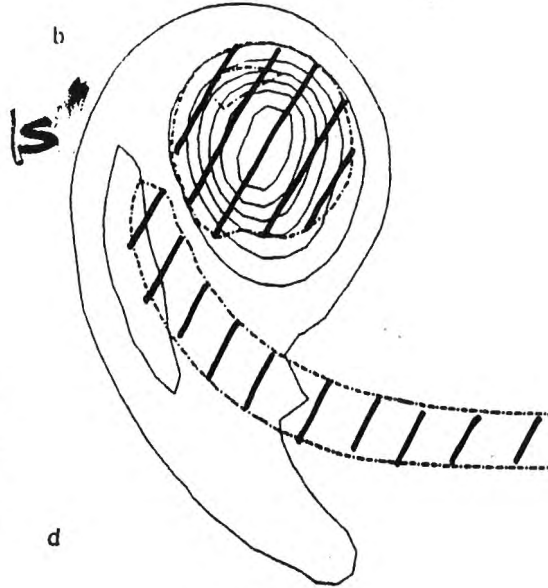
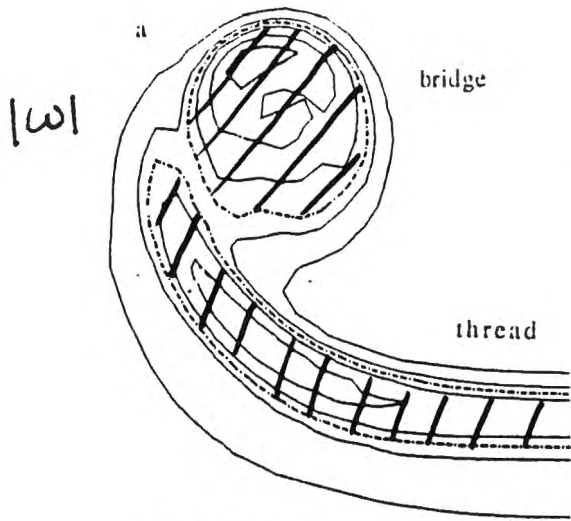
$\rightarrow -P_w$

Decreases peak w (9e, 10e)

" twist vel.

Shows eq A induces $u \parallel w$ in bridge

$t = 6$



h_r conditional relative helicity
(eliminate noise first.)

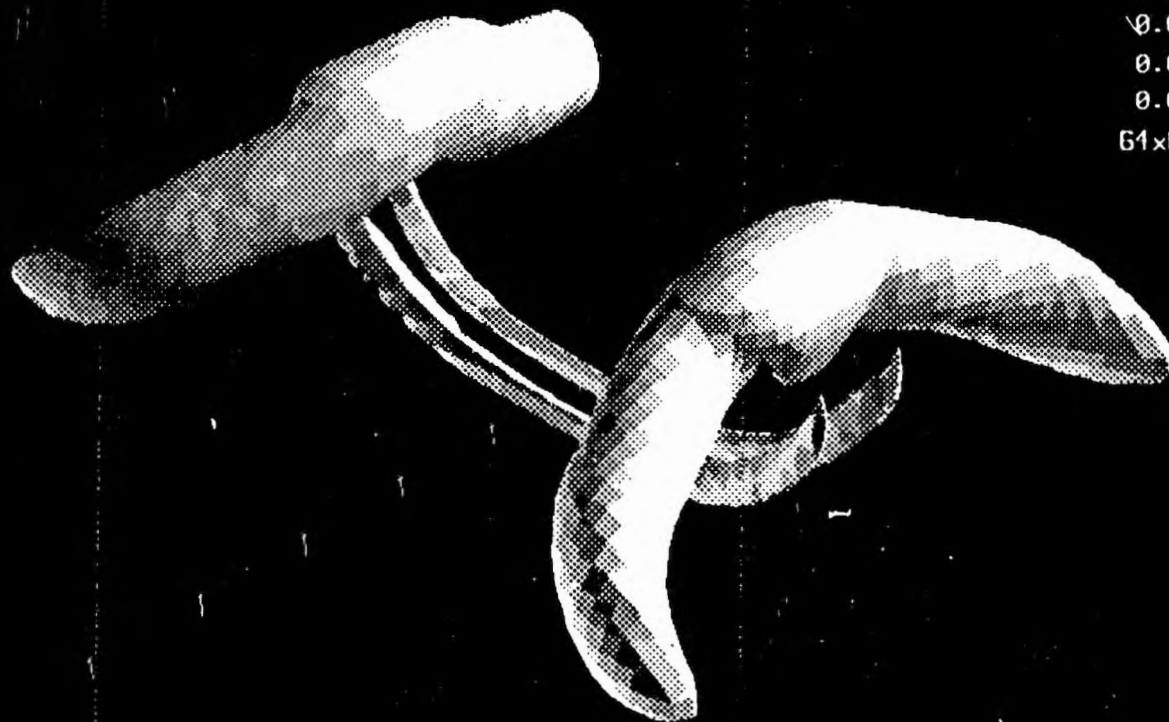
Figure 10. Plane cross-sections at $t=6.0$ (see caption from figure 8).

Go back

- 1) P_w +ve due to hairpin
- 2) Twist \rightarrow pumping \rightarrow -ve P_w .
inviscid vorticity pumping
- 3) Conditional helicity density
marks centre.
- 4) Make away from vorticity
- 5) helicity and dissipation \leftarrow no connection

Mixing, Cascade helicity

CONTOUR LEVELS
6.00000



0.00x10++0 N
0.00x10++0 III
0.00x10++0 Pr
0.00x10++0 Time
64x64x64 GP10

REVERSE. -> Successive reconnection scenario
-> a new cascade mechanism!

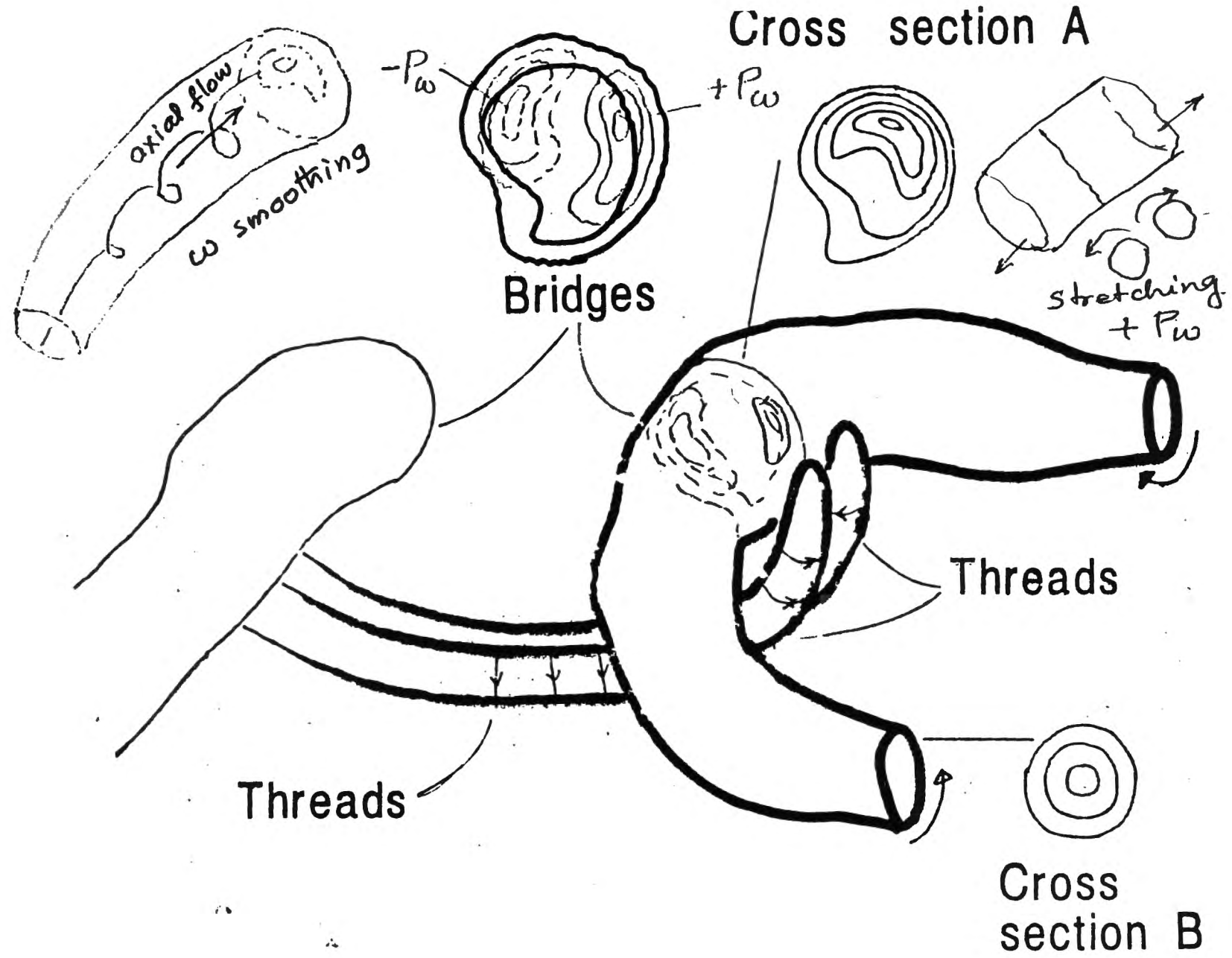
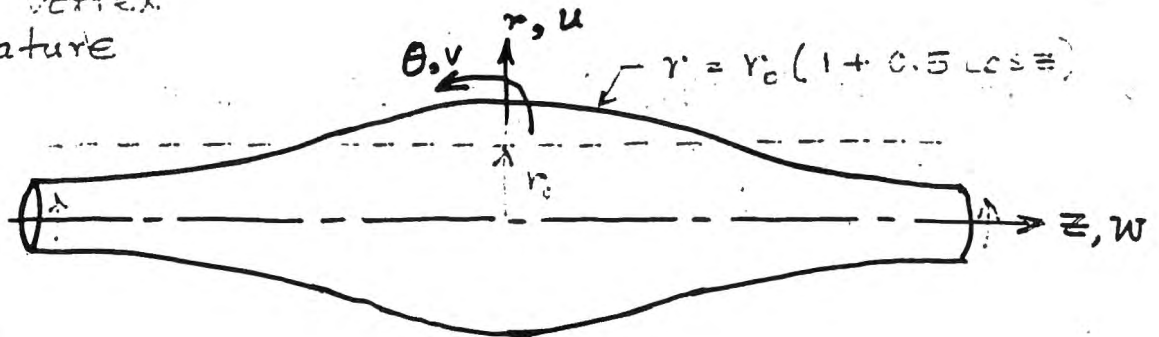


Fig. 1

idealized vortex
no curvature



Initial Condition: $S = r/r_0 = 1 + 0.5 \cos z$

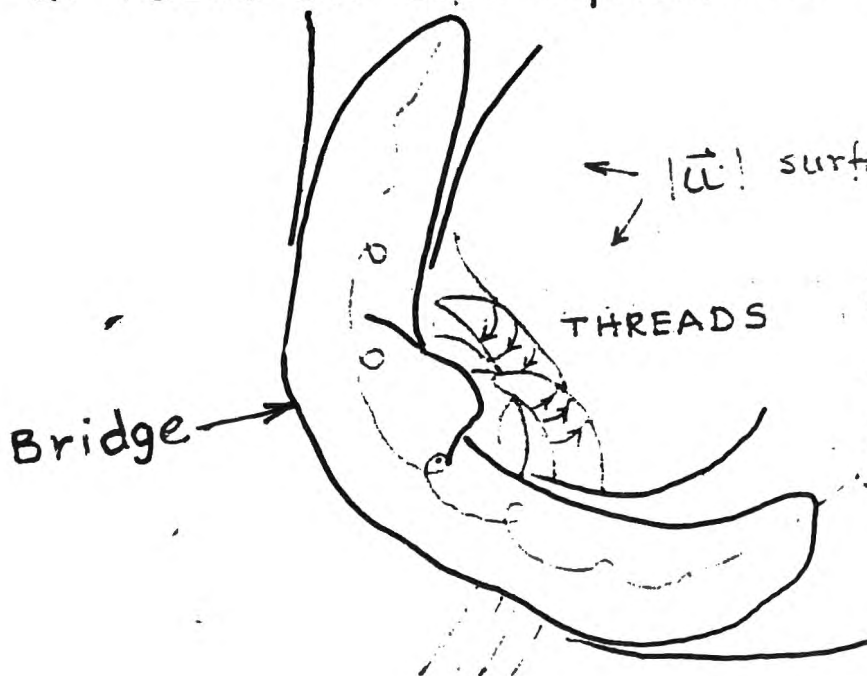
Core: $\omega = \omega_m e^{-4r^2/e^2}$

$t = 20/(\omega_m \cdot 10)$

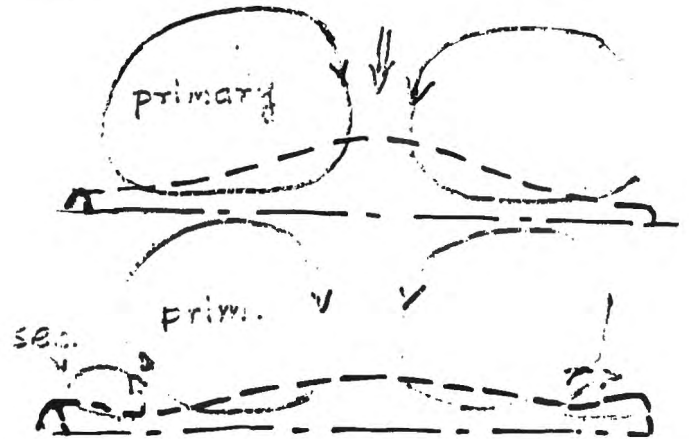
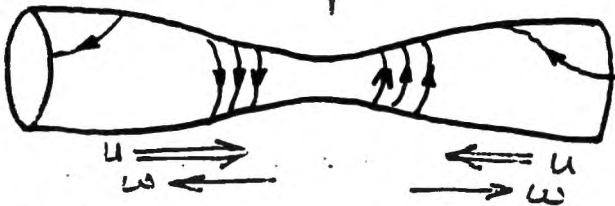
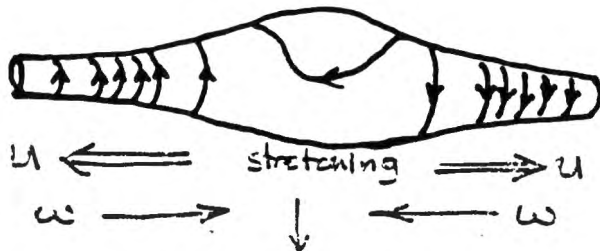
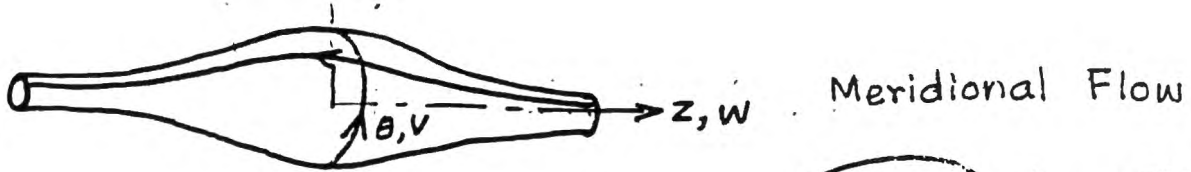
$Re \equiv \Gamma/\nu \approx 665$ (both lam. & turb.)

Motivations:

1. Nonuniform cores produced in reconnection: the bridges become uniform faster than diffusion mechanism: helical waves \neq axial flow.
2. Focus on core dynamics by axial flow.



- Simplify
- 1) straight vortex
 - 2) isolated vortex
 - 3) sinusoidal core
 - 4) No thread stretching
- ← VERT. line



$$D_t \xi = \text{viscous term}; \quad \xi \equiv rv$$

$$D_t \eta = \frac{1}{r^2} \frac{\partial (\xi^2)}{\partial z} + \text{viscous term}; \quad \eta \equiv \frac{w_\theta}{r} \leftarrow \begin{array}{l} \boxed{\text{swirl}} \\ \boxed{\text{meridional flow}} \end{array}$$

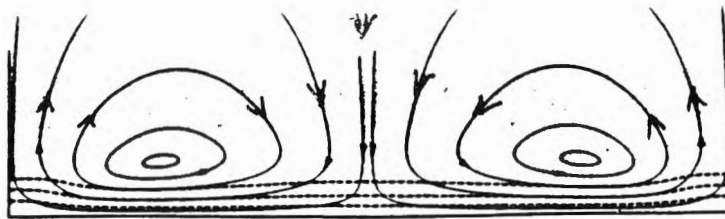
$$D_t = \partial_t + u\partial_r + w\partial_z \quad \text{deriv. in meridional flow}$$

$$\text{meridional flow: } u = \Psi_z / r, \quad v = -\Psi_r / z$$

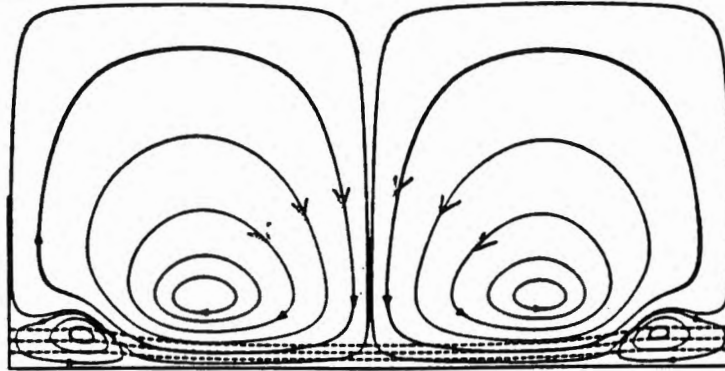
$$r w_\theta = \Psi_{rr} - \Psi_r / r + \Psi_{zz}$$

Azimuthal vorticity w_θ , initially zero, is generated by axial expansion and contraction. At small times, through the stretching term $\partial(\xi^2)/\partial z$. More details of the interaction between meridional and azimuthal flows are given in the next section.

Stream function ψ
for
meridional flow



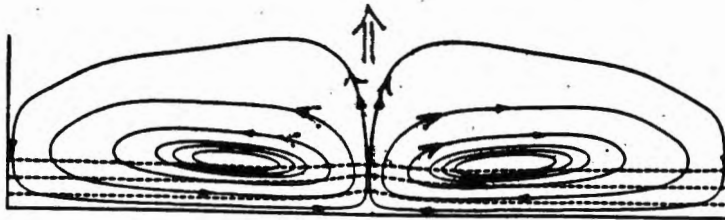
$t = 1$



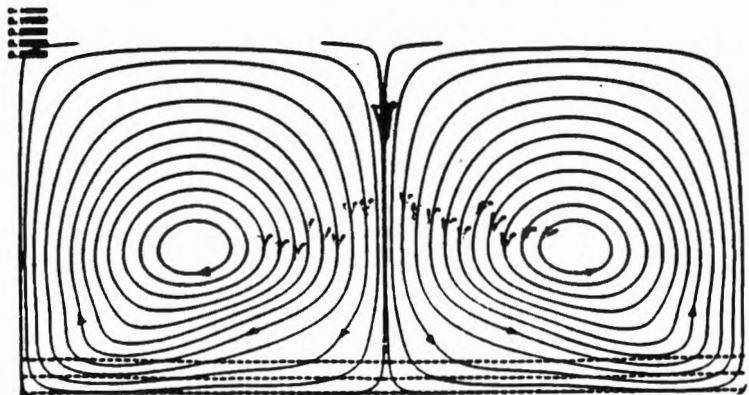
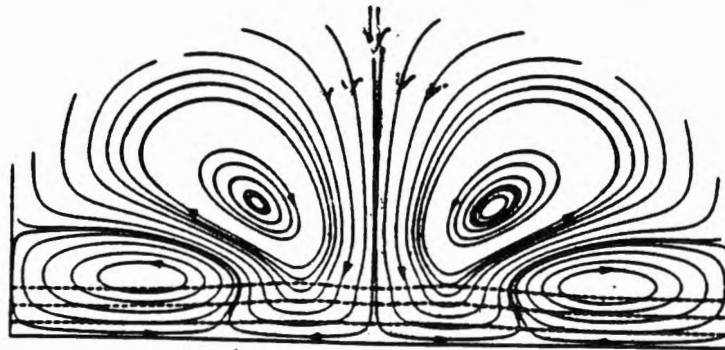
$t = 2$



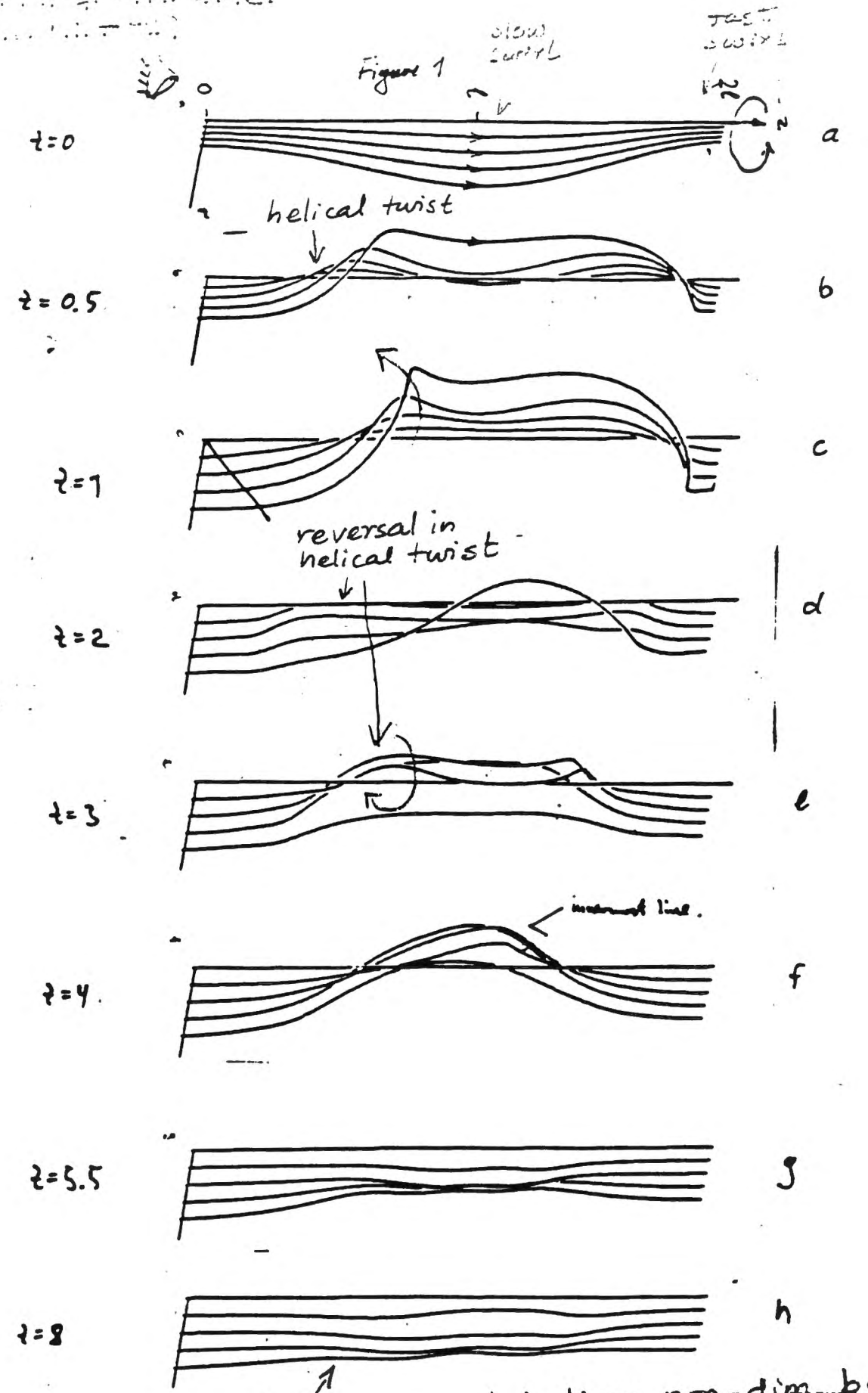
$t = 3$



$t = 4$



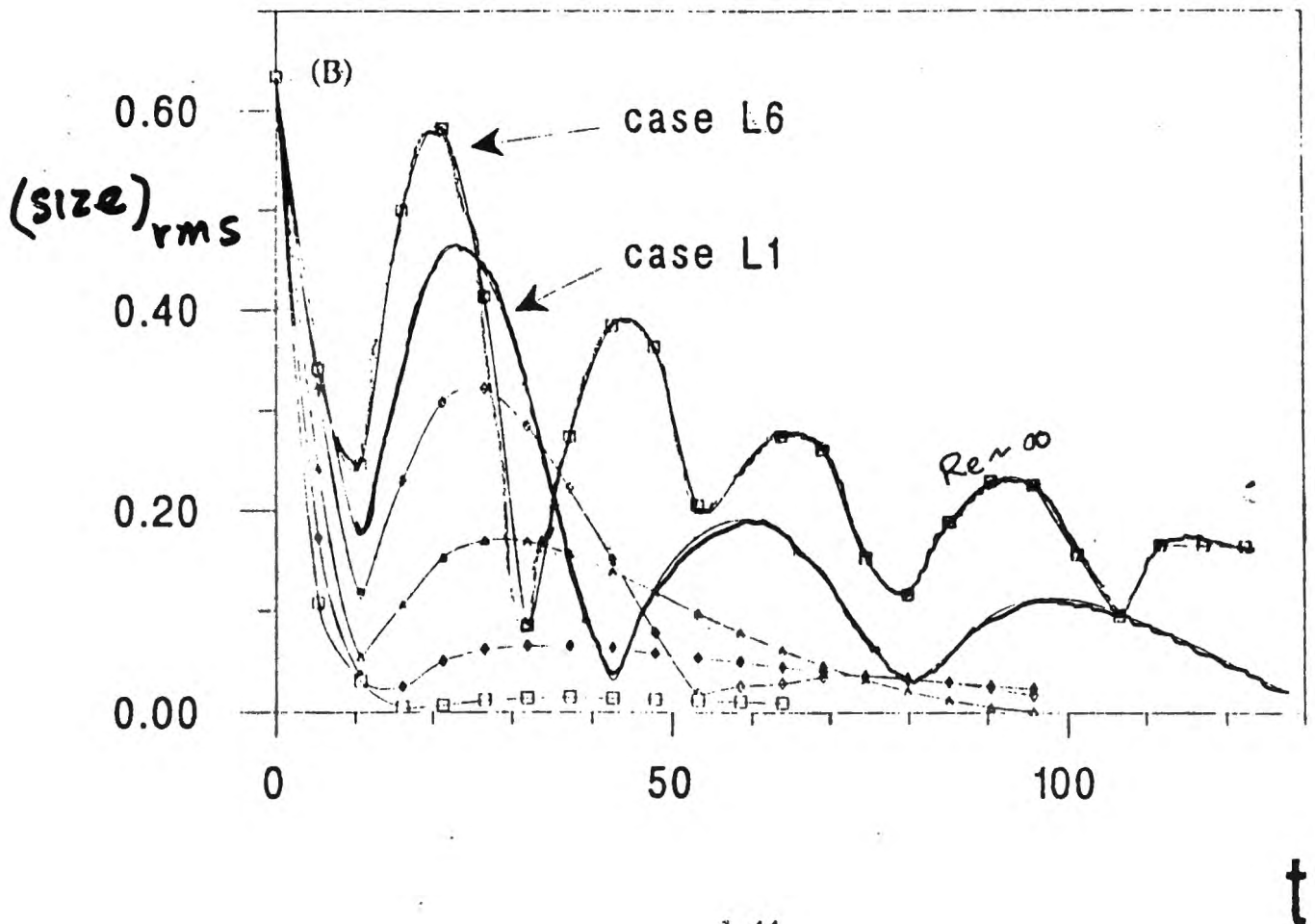
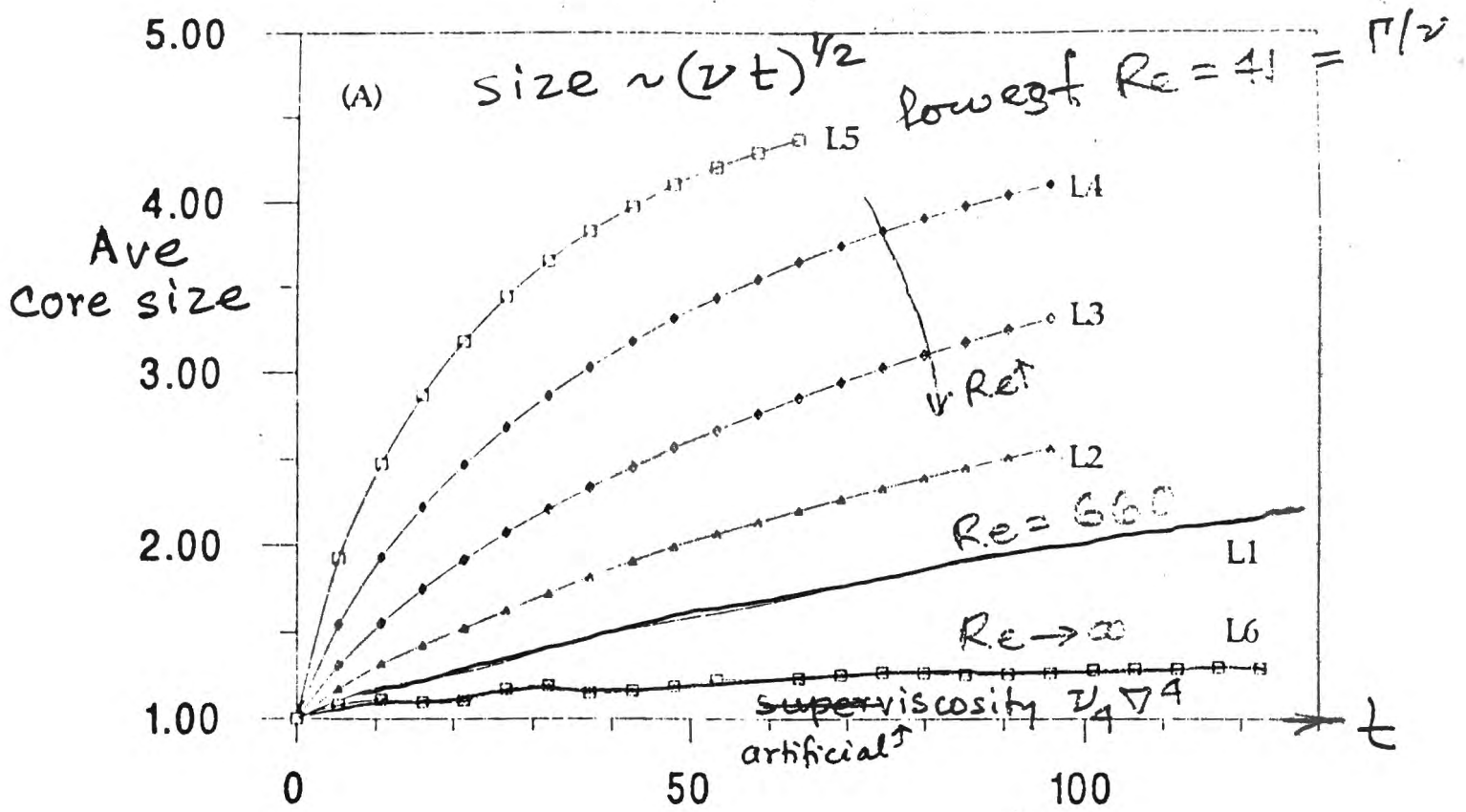
$\vec{v} = \vec{v}_0 + \vec{v}_1$
 $\vec{v}_1 = \vec{v}_0 \times \vec{z}$



up \vec{z}

almost damped core dyn.

t is time non-dim. by Γ
 and ang. impulse $\vec{M} = \int_{\mathbb{R}^3} \vec{r} \wedge \vec{v} dV$
 1-43



At what rate vortex core σ increase as a result of coupling bet. swirl & meridional and also entrainment?

Defn. of a vortex (controversial subject)

A kinematic defn. as a spatial connected region with $N_v \equiv [\omega^2 / 2 \epsilon \nu]^{1/2}$

$$\sigma_{uv} \sim (\nu t)^{1/2}$$

clearly viscous
not inviscid effect

Osc. f. inc. with Re
but with a finite limit as $Re \rightarrow \infty$

Important implication for reconnection

common belief recon. in one step

But due to threading, we claim recon. happens in bursts

As $Re \rightarrow \infty$, Γ trans. in each burst decreases while duration of each burst finite

i.e. $\Gamma_r \rightarrow 0$ as $Re \rightarrow \infty$

$\Rightarrow t_{rec.} \downarrow$ as $Re \uparrow$

$t_{burst} \rightarrow const.$ as $Re \rightarrow \infty$

Evol. of wavepackets, interactions
& core dynamics

can be explained by classical hydrodyn.
as coupling bet. swirl (ξ) & meridional flow (η)

Core dynamics \rightarrow helicity dynamics

Helicity

$$\vec{\omega} \cdot \vec{u}$$

$$|\vec{\omega} \wedge \vec{u}|^2 = |\vec{\omega}|^2 |\vec{u}|^2 - h^2 = |\vec{\omega}|^2 |\vec{u}|^2 (1 - h_r^2)$$

$$h_r \equiv \frac{\vec{\omega} \cdot \vec{u}}{|\vec{\omega}| |\vec{u}|}$$

$h_r \uparrow \Rightarrow \vec{\omega} \wedge \vec{u} \downarrow$
but $\nabla \wedge (\vec{\omega} \wedge \vec{u})$ can be large

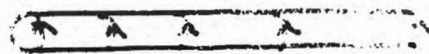
NSE
$$\vec{u}_\pm + \vec{\omega} \wedge \vec{u} = -\nabla \left(\frac{p}{\rho} + \frac{u^2}{2} \right) + \nu \Delta \vec{u}$$

If Lamb vector $\vec{\omega} \wedge \vec{u}$ not solenoidal (i.e. only potential)

$$\Rightarrow \vec{\omega}_\pm = \nu \Delta \vec{\omega} \quad \text{NO CASCADE}$$

Thus $h_r = \pm 1$ (Beltramiization) sufficient, not necessary for cascade suppression

Example: rectilinear vortex
no axial flow.



$\vec{\omega} \wedge \vec{u}$ large but purely potential

h, h_r , not being Galilean invariant (Spiegel 77),
is not a useful quantity in turbulence
(Rozenski & Moin).

Alternative approach: Helical Wave Decomposition
Moses (71), Lesieur (86)

Lamb vector $|\omega \wedge u|^2 = \omega^2 u^2 (1 - h_r)$

$\omega \wedge u$ is the NL term and responsible for cascade
(i.e. trans. to ss)

Expect small cascade if $h_r \approx 1$

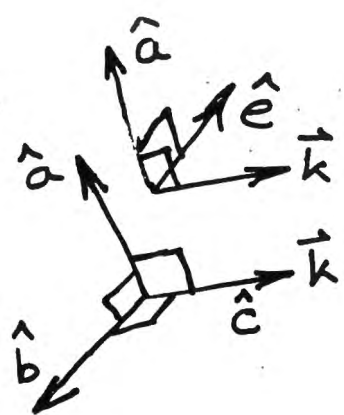
If $h_r = 1$, $\omega \wedge u = 0$ sufficient for cascade suppression
 If $h_r \neq 1$, then $\omega \wedge u \neq 0$ hence though nonzero, can be potential
 still complete cascade suppression.
 Hence $h_r = 1$ is sufficient but not necessary.

3. If cascade is suppressed (as in rect. vortex)
 $\rightarrow h_r \neq \pm 1$ (actually zero)

4. In a particular frame, $h_r = 0 \rightarrow$ but $\omega \wedge u$
 can be large but purely potential
 so vort. eqn. \rightarrow diffusion eqn.
 i.e. no cascade

5. Thus $h_r = \pm 1$ (Beltramiization) is
 sufficient, but not necessary.

Complex Helical Wave Decomposition



Let \hat{e} any arbitrary fixed unit vector

For each \vec{k} in Fourier space, introduce

$$\hat{a}(\vec{k}) = \frac{\vec{k} \wedge \hat{e}}{|\vec{k} \wedge \hat{e}|}; \quad \hat{b}(\vec{k}) = \frac{\vec{k} \wedge \hat{a}}{|\vec{k} \wedge \hat{a}|}; \quad \hat{c}(\vec{k}) = \frac{\vec{k}}{k}$$

\hat{e} only helps introduce orthonormal basis $\{\hat{a}, \hat{b}, \hat{c}\}$

\Rightarrow any vector function $\vec{F}(\vec{x})$ is divergence free if its Fourier coeff. $\vec{F}^+(\vec{k})$ is $\perp \vec{k}$ (i.e. $\vec{k} \cdot \vec{F}^+ = 0$)
i.e. \vec{F}^+ must be a linear comb. of \hat{a} & \hat{b} .

can show that 'complex helical waves'

$$\vec{V}^+(\vec{k}, \vec{x}) = [\hat{b} - i\hat{a}] e^{i\vec{k} \cdot \vec{x}}$$

$$\vec{V}^-(\vec{k}, \vec{x}) = [\hat{b} + i\hat{a}] e^{i\vec{k} \cdot \vec{x}}$$

are orthogonal eigenfunctions of curl operator:

$$\nabla \wedge \vec{g} = \lambda \vec{g} \quad \text{where } \lambda = \pm k$$

Now, velocity (\vec{u}) and vorticity ($\vec{\omega}$) can be expressed as sum of right and left handed components: \vec{V}^+, \vec{V}^-

$$\vec{u}(\vec{x}, t) = \vec{u}_R + \vec{u}_L = \sum_{\vec{k}} u^+(\vec{k}, t) \vec{V}^+(\vec{k}, \vec{x}) + \sum_{\vec{k}} u^-(\vec{k}, t) \vec{V}^-(\vec{k}, \vec{x})$$

$$\vec{\omega}(\vec{x}, t) = \vec{\omega}_R + \vec{\omega}_L = \sum_{\vec{k}} k u^+(\vec{k}, t) \vec{V}^+(\vec{k}, \vec{x}) + \sum_{\vec{k}} k u^-(\vec{k}, t) \vec{V}^-(\vec{k}, \vec{x})$$

\uparrow
Correspond to $+\lambda$

\uparrow
Correspond to $-\lambda$

we will study terms by a relation of right and left handed waves at propagation.

$$\vec{\omega} = \vec{\omega}_R + \vec{\omega}_L$$

Coupling of $\vec{\omega}_R$ and $\vec{\omega}_L$ better understood using projection operators P^+ , P^-

Applying to N-S Eqn: $\frac{\partial \vec{\omega}}{\partial t} + \vec{\omega} \wedge \vec{u} = -\nabla \left(\frac{p}{\rho} + \frac{u^2}{2} \right) + \nu \Delta \vec{u}$

$$\Rightarrow \frac{\partial \vec{\omega}_R}{\partial t} = -P^+(\nabla \wedge (\vec{\omega} \wedge \vec{u})) + \frac{\nu}{Re} \Delta \vec{\omega}_R$$

Rewrite for physical interpretation

$$\frac{\partial \vec{\omega}_R}{\partial t} = -\nabla \wedge (\vec{\omega}_R \wedge \vec{u}_R)$$

$$+ P^- [\nabla \wedge (\vec{\omega}_R \wedge \vec{u}_R)]$$

$$+ P^+ [(\vec{u}_L \cdot \nabla) \vec{\omega}_R]$$

$$+ P^+ [(\vec{\omega}_R \cdot \nabla) \vec{u}_L]$$

$$- P^+ [\nabla \wedge (\vec{\omega}_L \wedge \vec{u})]$$

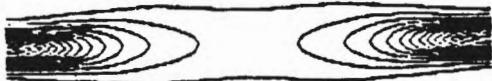
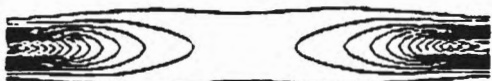
$$+ \frac{\nu}{Re} \Delta \vec{\omega}_R$$

- | | | |
|------|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2nd | Terms | 1: inviscid self-evol. of $\vec{\omega}_R$ |
| 5th | | 2: gen. of $\vec{\omega}_L$ by evol. of $\vec{\omega}_R$ |
| Most | | 3: contrib. to $\vec{\omega}_R$ by its adv. by \vec{u}_L |
| dom | | 4: $\vec{\omega}_R$ gen. by its stretching by \vec{u}_L |
| 4th | | 5: $\vec{\omega}_R$ growth by evol. of $\vec{\omega}_L$: includes ω_R gen. by evol. by of ω_L + right handed contrib. from stretching and adv. of ω_L by u_R |
| 3rd | | 6: viscous diff. of ω_R |

last
Ret

$|\omega_{LEFT}|$

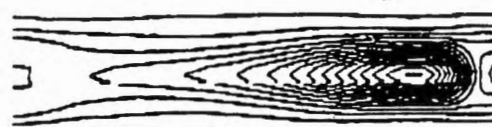
$|\omega_{RIGHT}|$



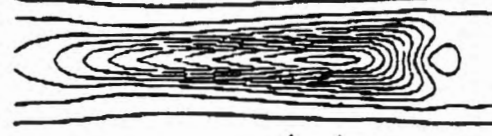
$t=0.$



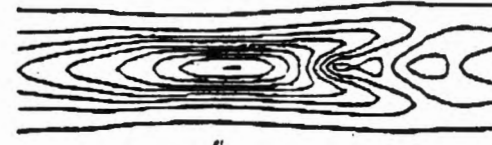
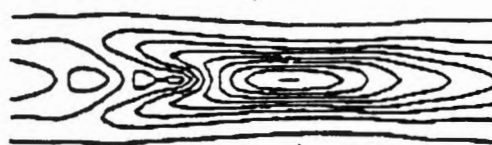
$t=0.5$



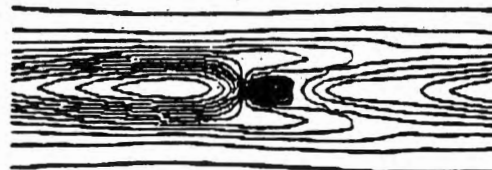
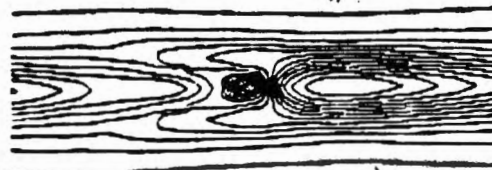
$t=1.0$



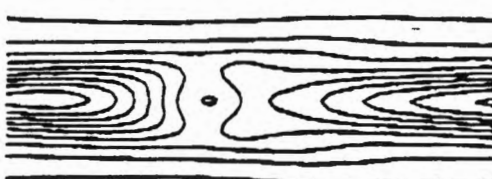
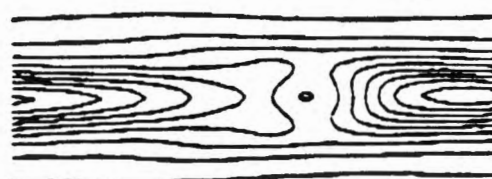
$t=2.0$



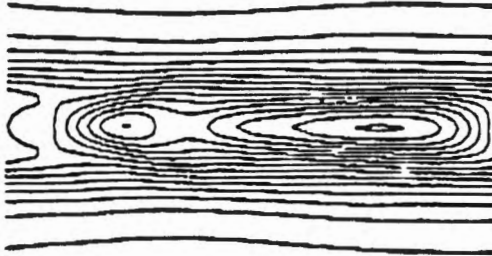
$t=3.0$



$t=4.0$

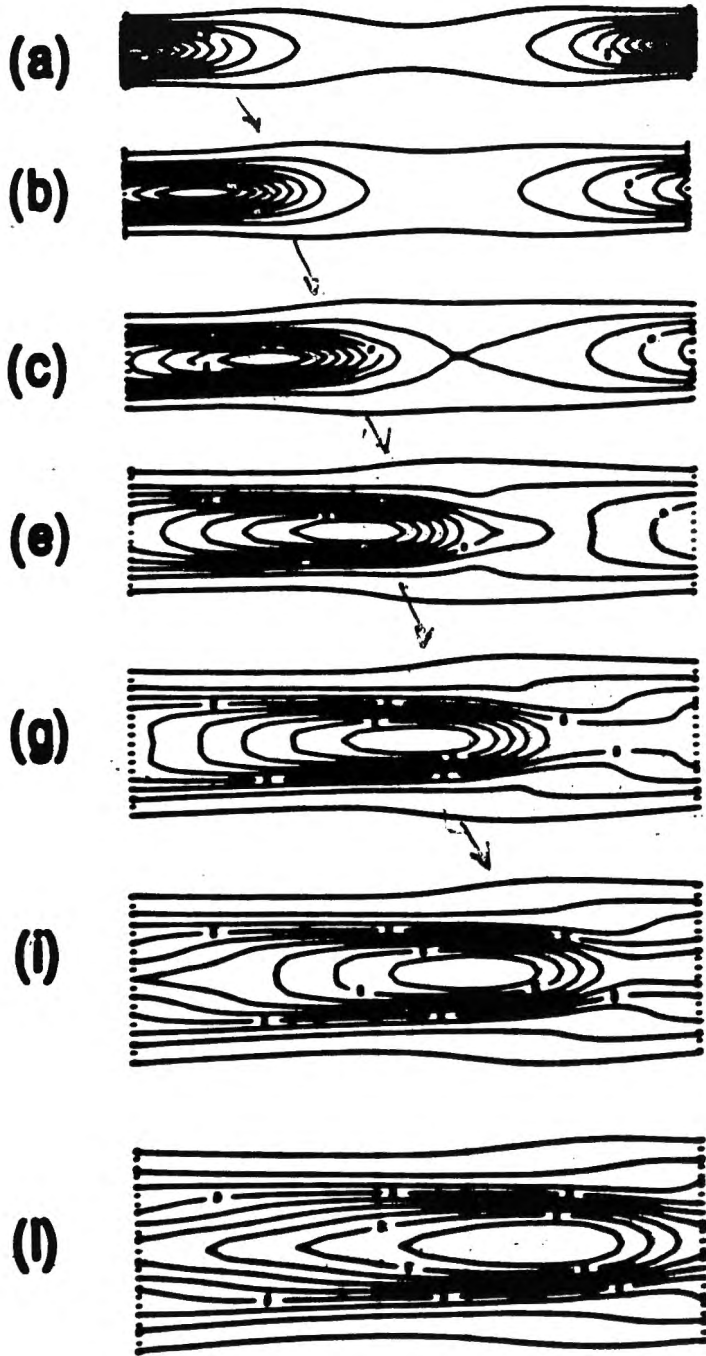


$t=5.5$



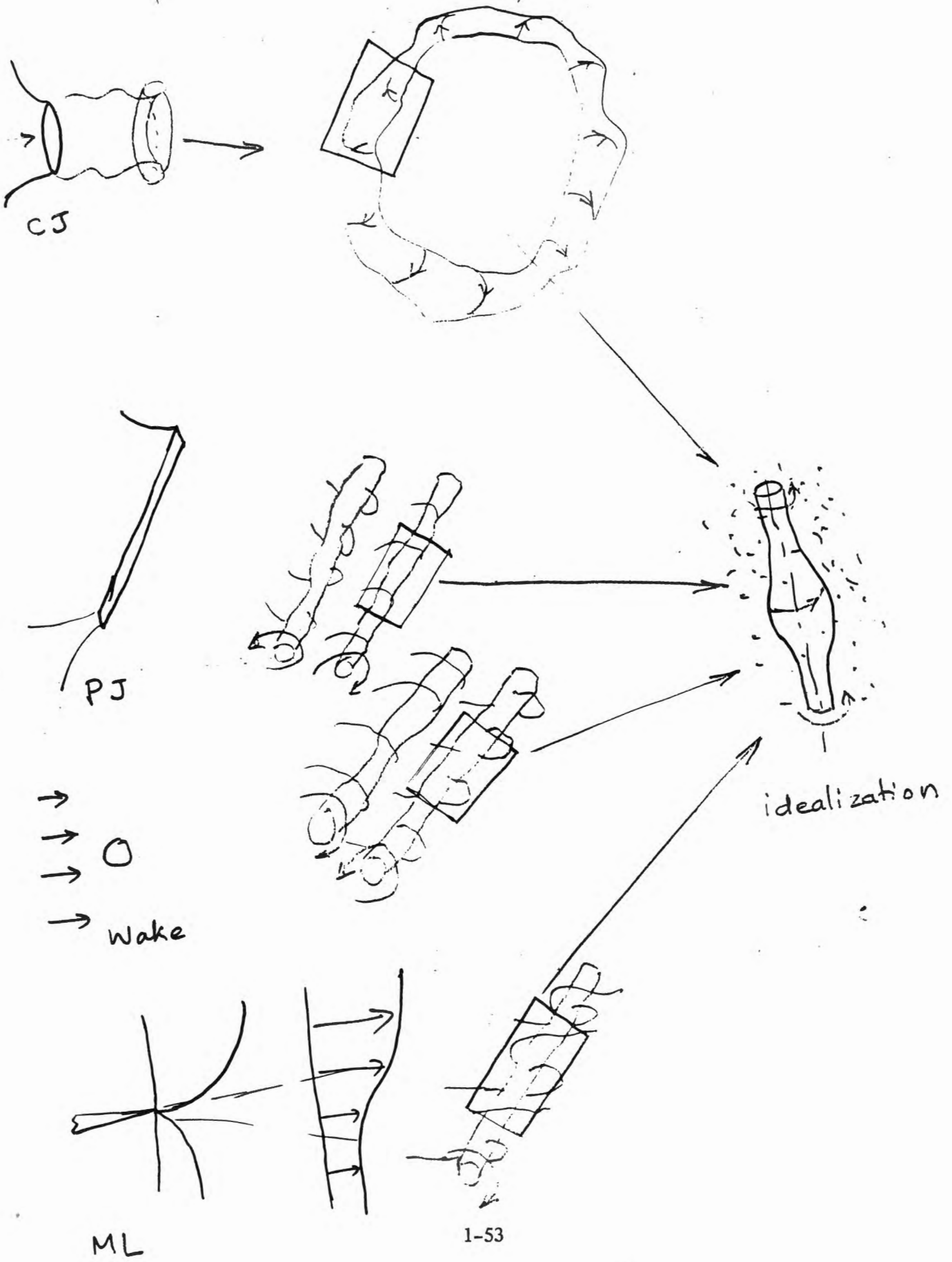
$t=8.0$

initially $\vec{\omega}_R$ only



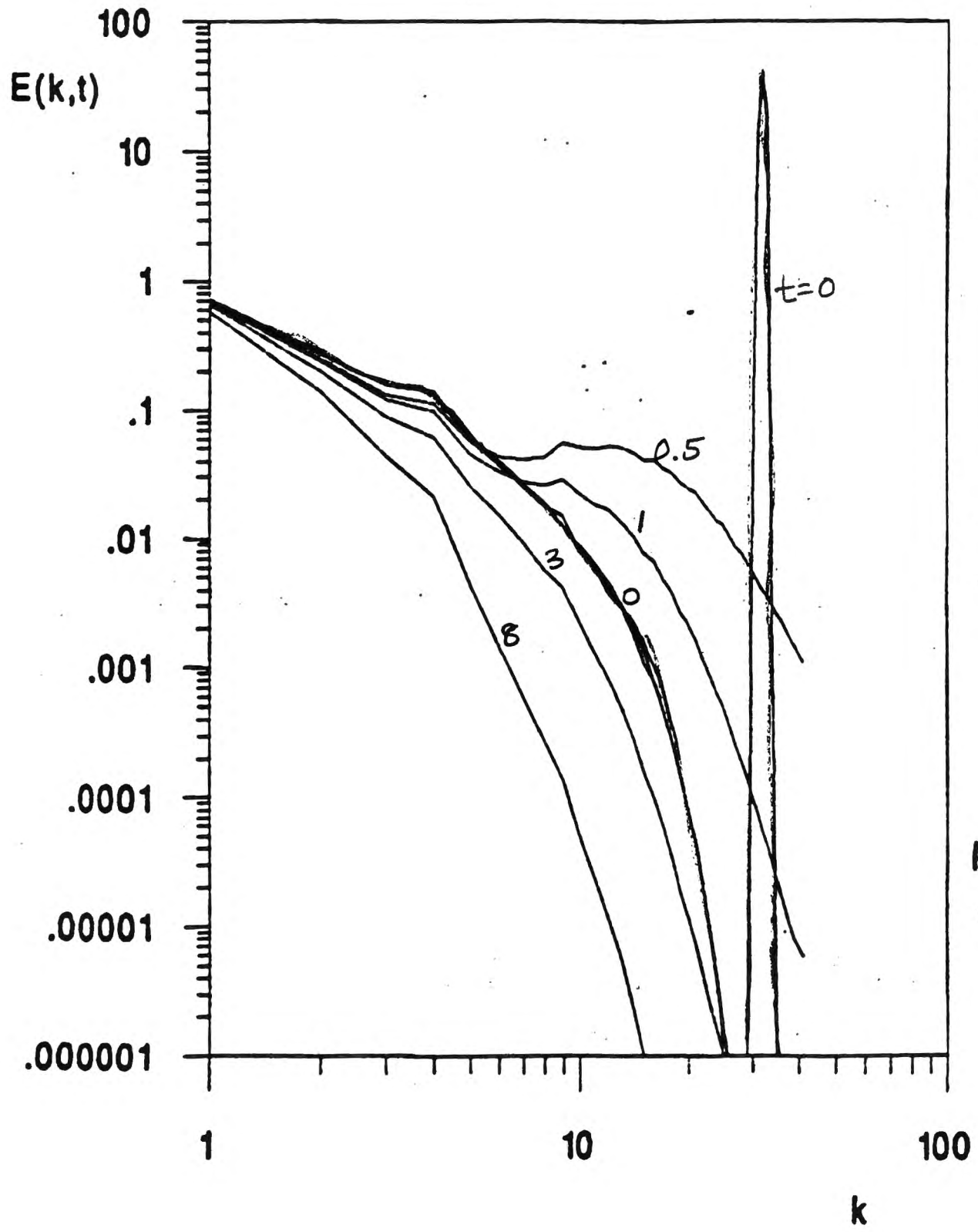
$\vec{\omega}_R$ vorticity at $t=0$
becomes $\vec{\omega}_R$ & $\vec{\omega}_L$
complex!

Fig. 19



Energy Spectra for Case T1

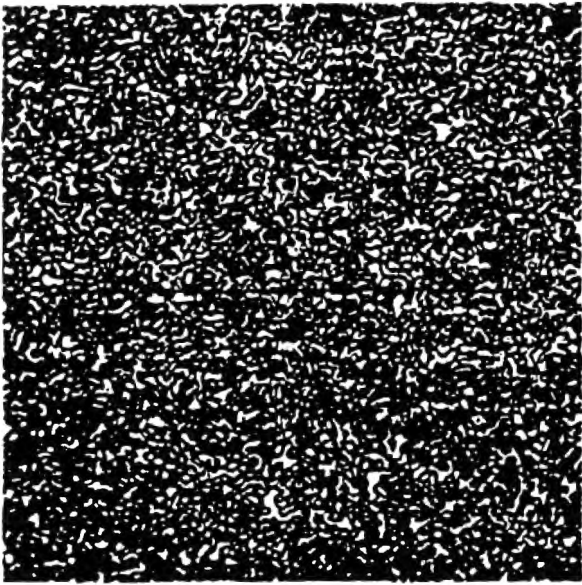
spectral gap @ $t=0$



$Re = \frac{U}{\nu}$
 $= 665$

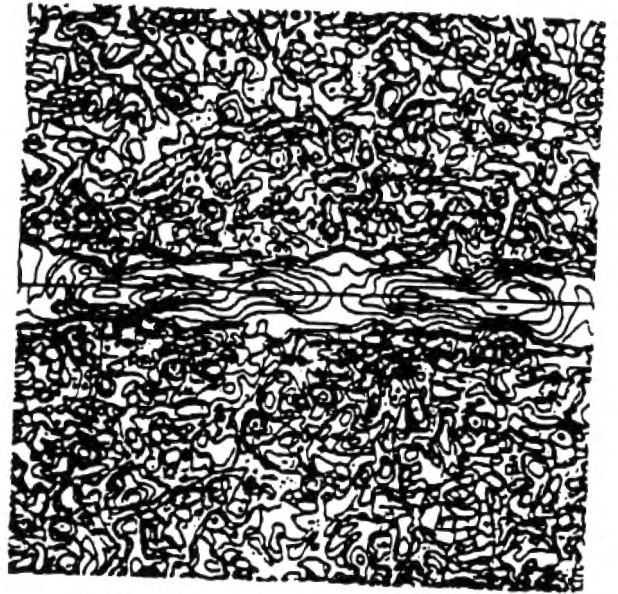
(a)

$t=5$



(c)

$t=1$



(g)

$t=3$



(q)

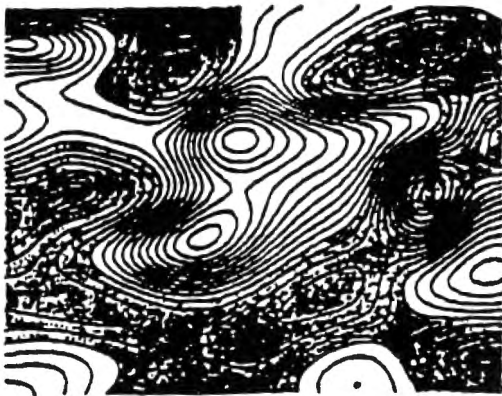
$t=8$



$|\omega|$ contours

SS growth and strongest @ C.S boundary

SS Organization by pairing



(2)



3



6



Fig. 33

(1)





1-59

1-59

6



1-60



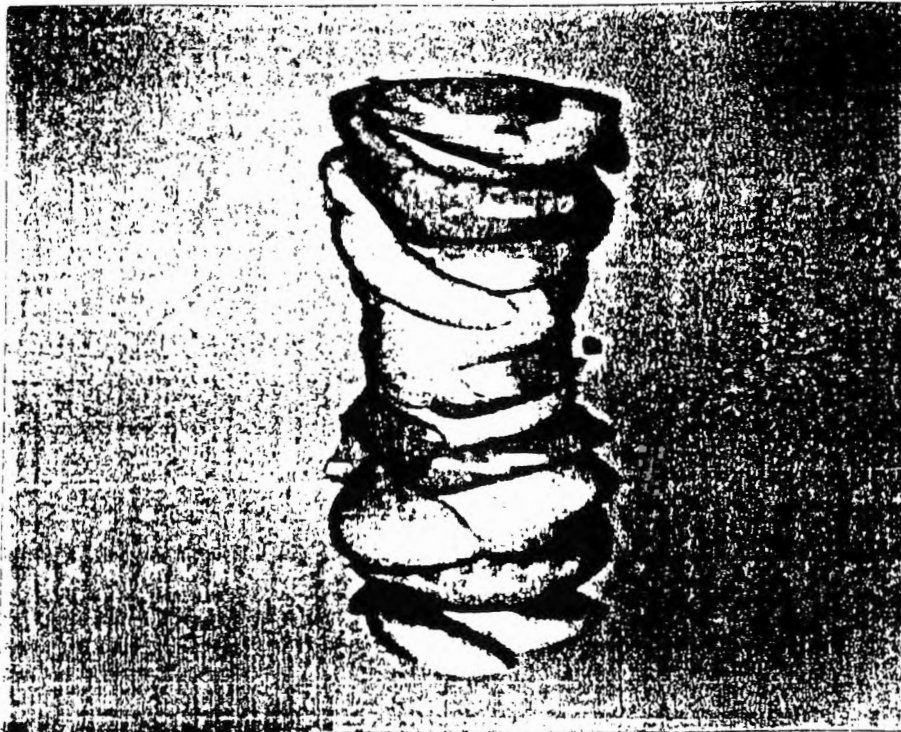


Left - normal |w|

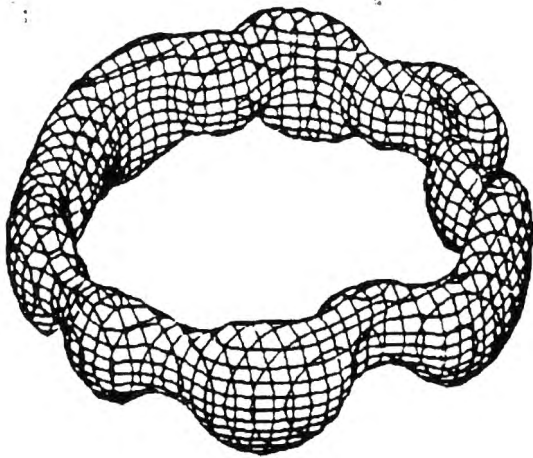


Right - 6 in 100 |w|

total



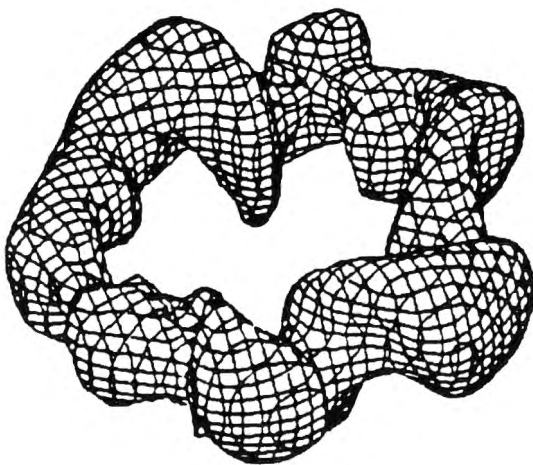
Circular Jet Simulation : Time $t=17$



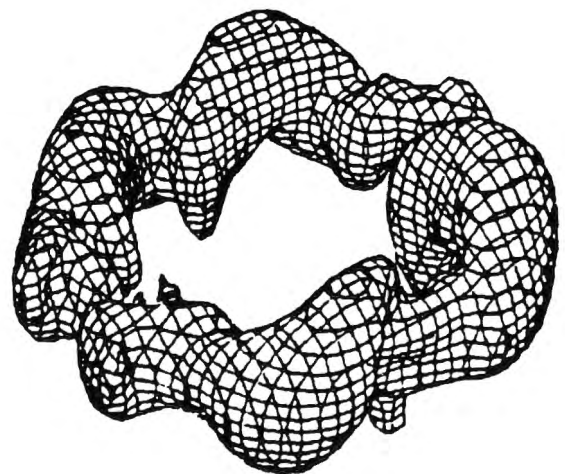
Isovorticity surface, $|\omega|=2$



Superposed isosurfaces of right- and left-handed helical vorticity

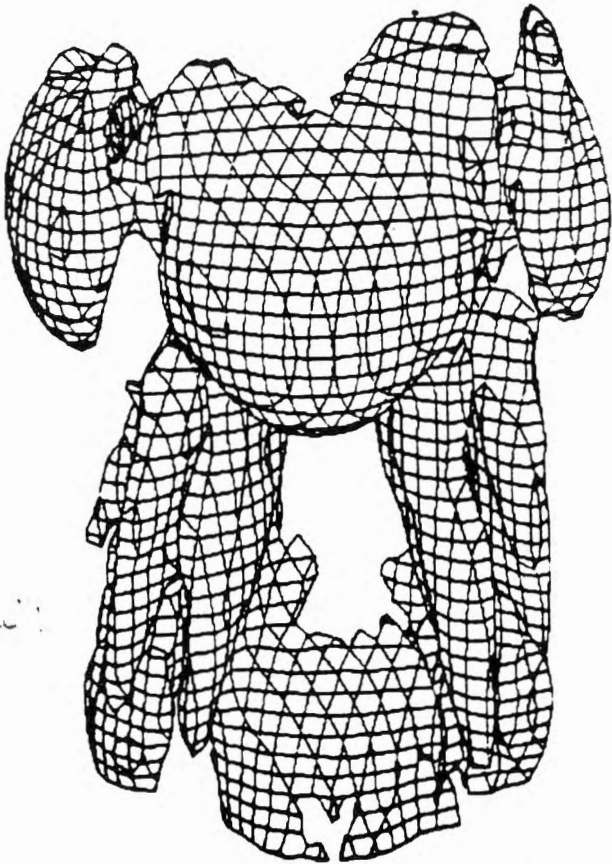


Isosurface of left-handed helical component of vorticity, $|\omega_L|=1.1$

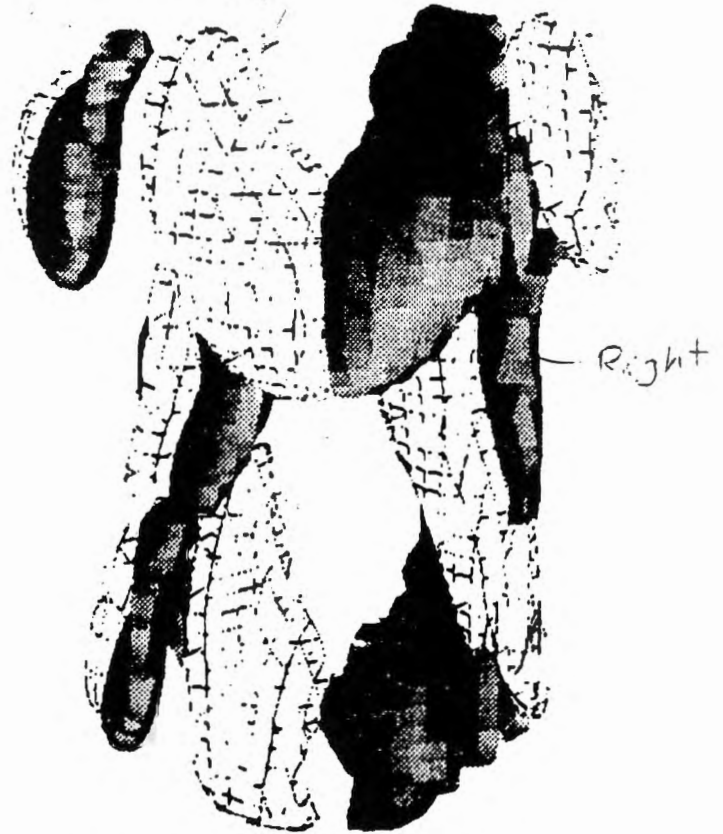


Isosurface of right-handed helical component of vorticity, $|\omega_R|=1.1$

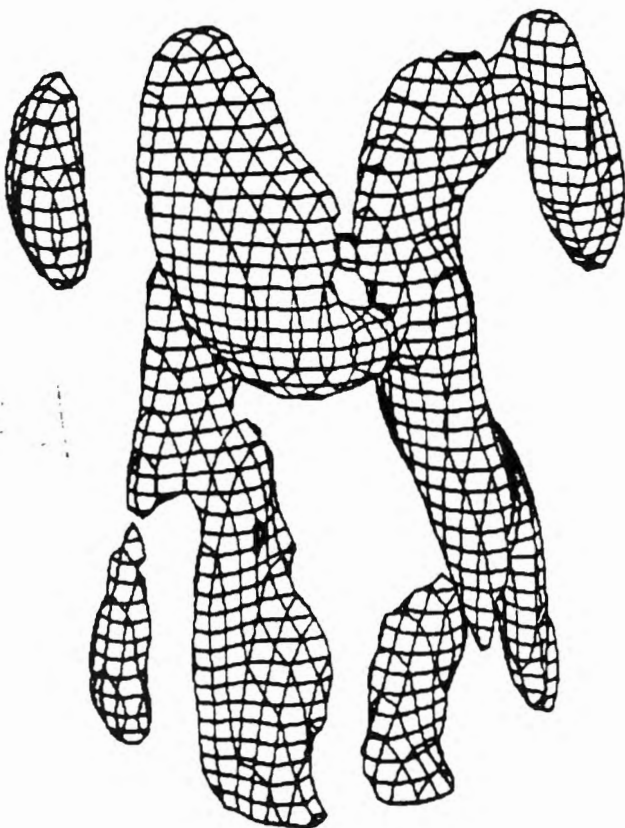
Circular Jet Simulation : Time $t=23$



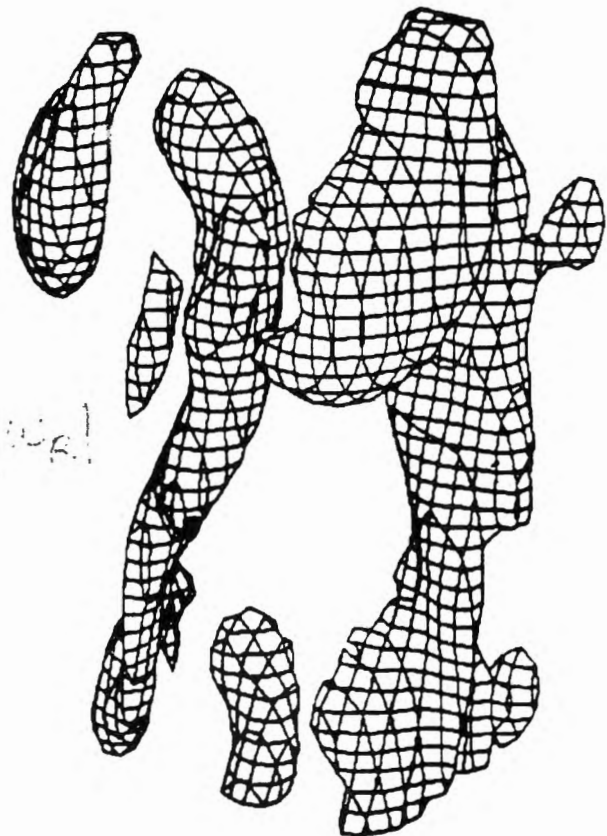
Isovorticity surface, $|\omega|=2$



Superposed isosurfaces of right- and left-handed helical vorticity



Isosurface of left-handed helical component of vorticity, $|\omega_L|=1.6$



Isosurface of right-handed helical component of vorticity, $|\omega_R|=1.6$

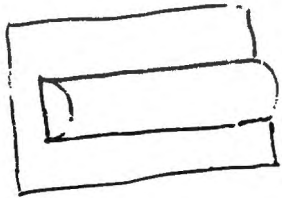


Fig. 24



Fig. 25

(1)



(9)

$|u|$ contours

$$r/\nu = 665$$

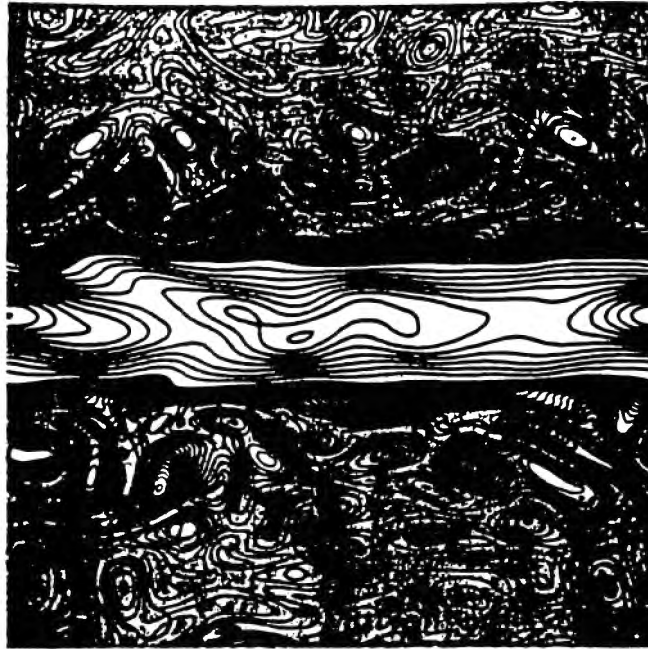
$$t = 8$$



Fig. 23

(A)

$\Gamma/\nu = 2500$
after $t \approx 8$
 $\Delta t = 4$



(B)

$\Gamma/\nu \approx \infty$
after $t = 8$
 $\Delta t = 4$



Fig. 37



$Re = \infty$

(A)



$Re = 2500$

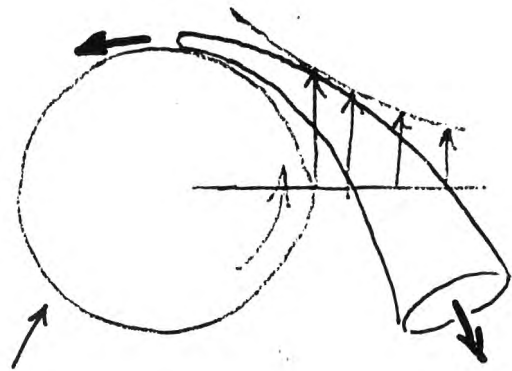
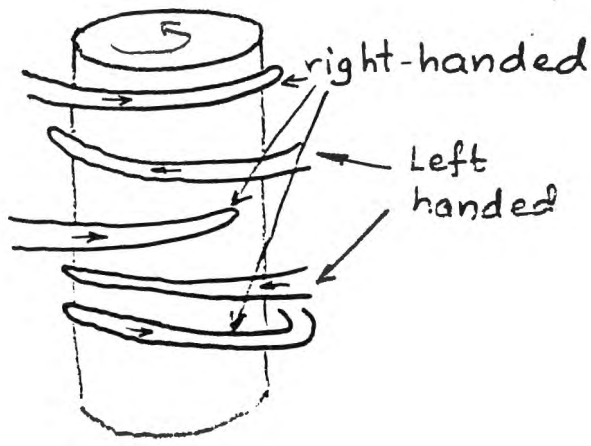
(B)



$Re = 665$

(C)

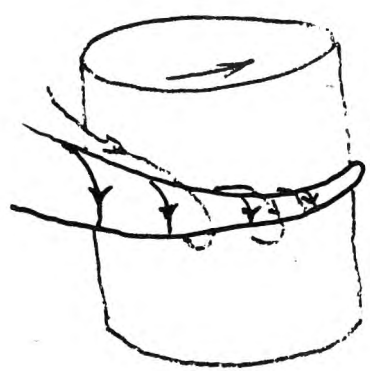
Fig. 38



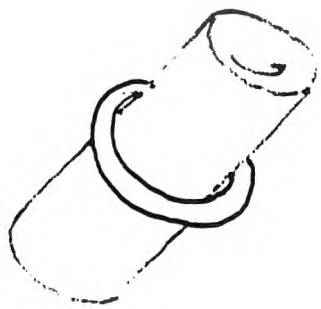
polarization
by stretching



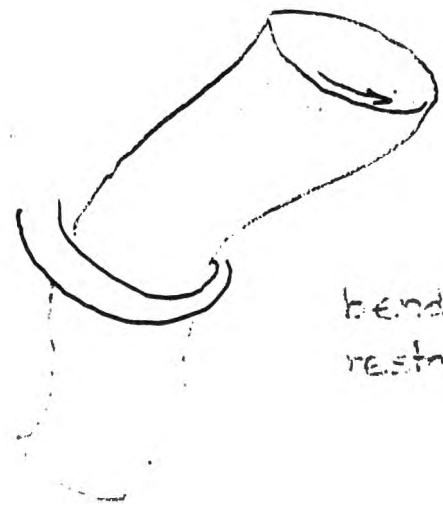
right & left
polarization



entrainment
by ss
growth of ss by
pairing & ext.

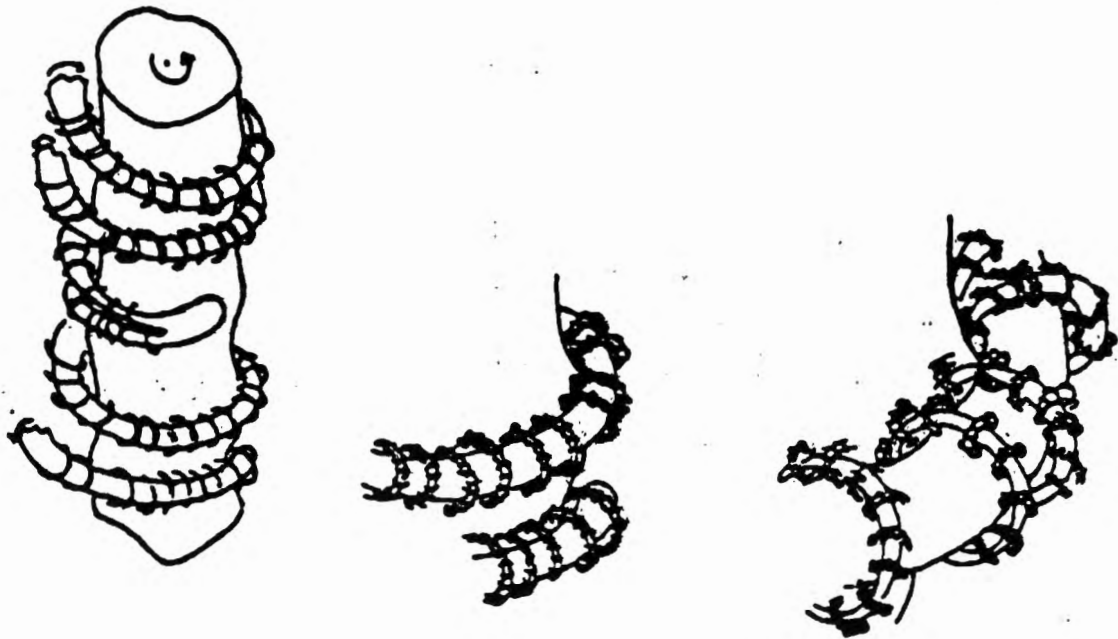


no stretching
of ss



bending waves
restrict stretching

A cascade scenario



A hierarchy of smaller structure (fractal)

LS preferentially oriented \rightarrow also SS;

local isotropy questionable.

$|\omega|$ and ϵ fractal structure

Helical waves (right and left handed)
separate spatially

They characterize CS

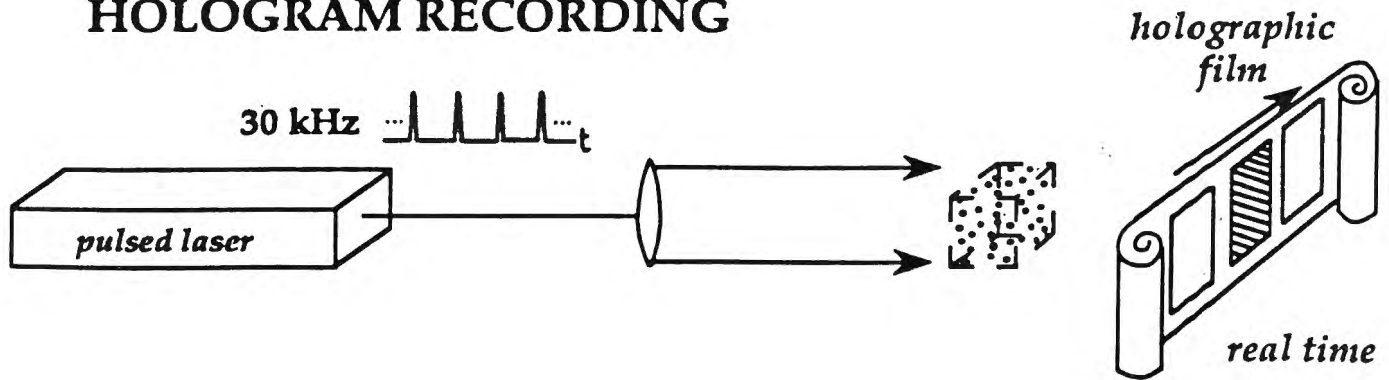
Breakdown to turbulence is
more organized than presumed.

Planning expts

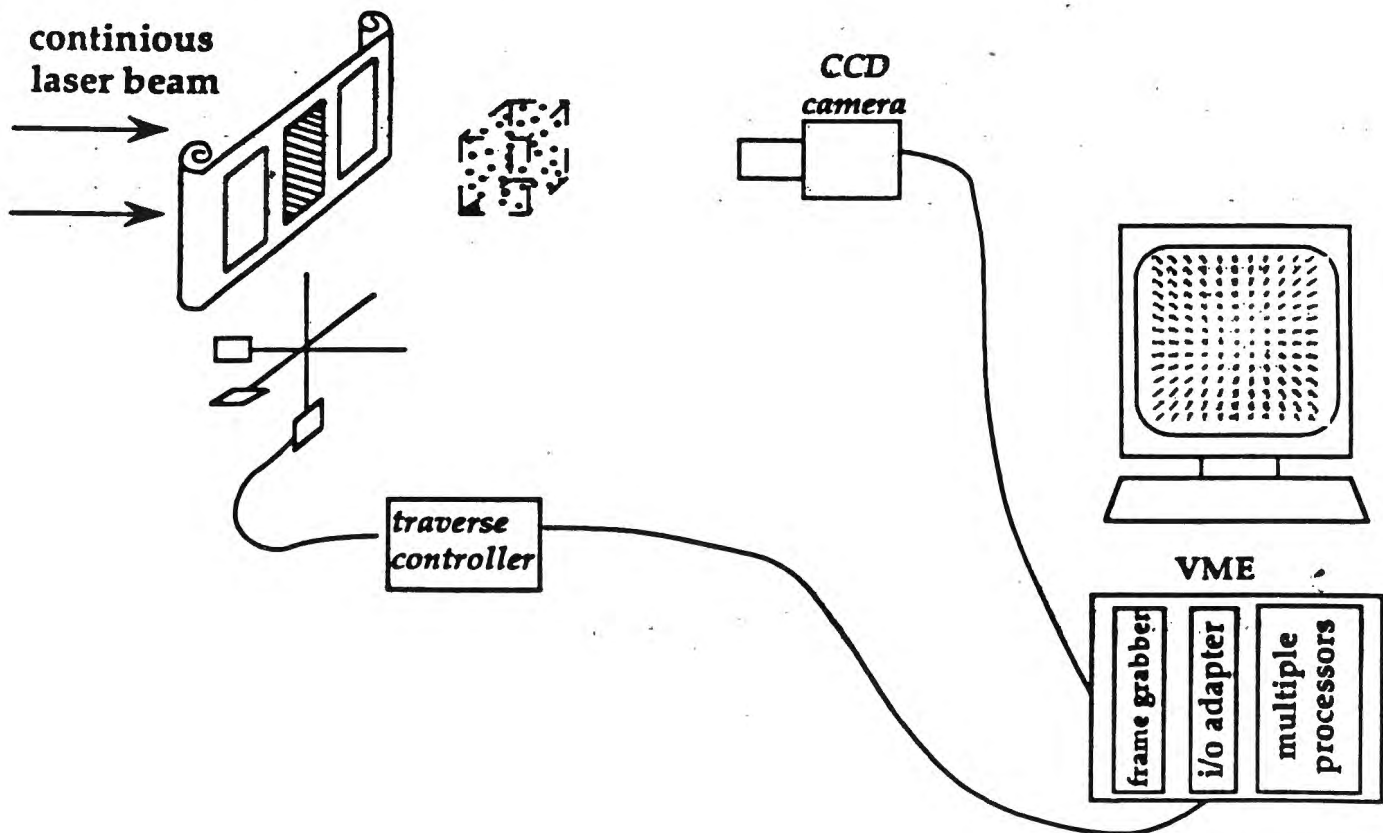
using holographic particle velocimetry
ESR velocimetry

Holographic Particle Velocimetry

HOLOGRAM RECORDING



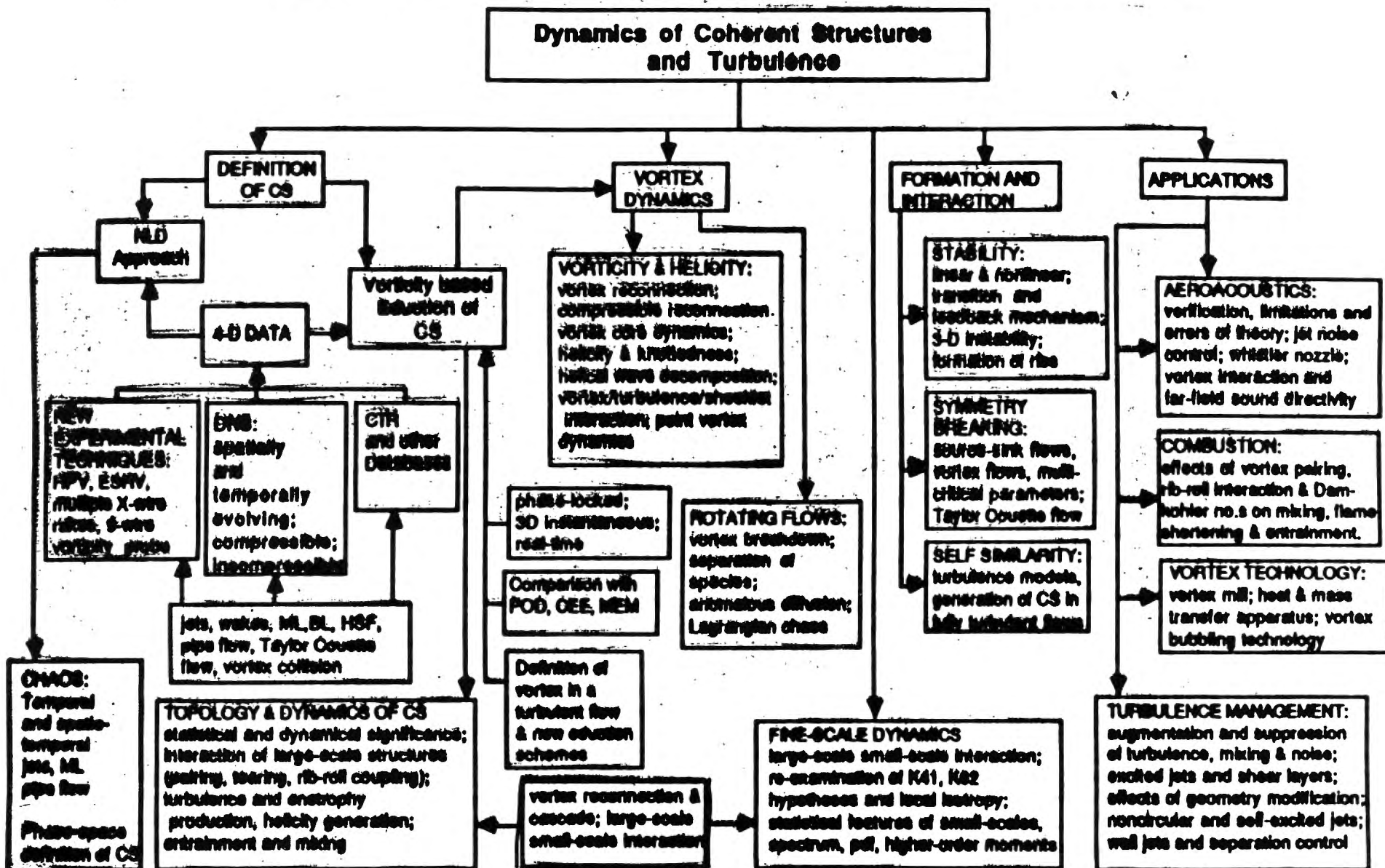
RECONSTRUCTION & DATA PROCESSING



Some conclusions

1. Core dynamics very important
2. Nonuniform Core size sets up wavepackets moving faster at higher Re , $freq \rightarrow const.$ as $Re \rightarrow \infty$
3. CS can be explained qualitatively by coupling of swirl and meridional flow
4. But complex helical wave decomposition (HD) is more effective; explains CS evolution better
5. CS organizes SS turb. into polarized structures which entrain and spatially grow (by pairing) and separate into left and right handed struct.
6. SS can feedback energy to CS by exciting bending waves, thus their own survival.
7. LS/SS (conceding scale separation) are intimately coupled: question local isotropy.

Aerodynamics & Turbulence Laboratory, University of Houston



1-74

Abbreviations: BL - Boundary Layer; CEE - Conditional Eddy Estimation; DNS - Direct Numerical Simulation; ESRV - Electron Spin Resonance Velocimetry; HPV - Holographic Particle Velocimetry; HSF - Homogeneous Shear Flow; K41, K42 - Kolmogorov's 1941 & 1962 hypotheses for turbulence; MEM - Maximum Entropy Method; ML - Mixing Layer; NLD - Nonlinear Dynamics; POD - Proper Orthogonal Decomposition

2. Renormalization Group Theory for Turbulence Transport Modeling

**Steven A. Orszag
Princeton University**

SEMINAR NOTICE

**RENORMALIZATION GROUP THEORY FOR
TURBULENCE TRANSPORT MODELING**

STEVEN A. ORSZAG

Hamrick Professor of Engineering and

Director and Professor of Applied and Computational Mathematics

Princeton University

In this talk, we shall describe the development and application of renormalization group (RNG) turbulence transport models with non-equilibrium rate-of-strain effects included. A wide variety of examples will be given, including turbulent flows, heat transfer, and pre-mixed combustion in step, cylinder, turn-around bend, valve, constricted pipe, blunt plate, and other geometries. The robustness of the modeling for massively separated, non-equilibrium, and swirling flows will be discussed. The relationship of transport modeling to full Navier-Stokes solutions and large-eddy simulations will also be discussed, especially in the context of describing coherent structure dynamics.

Thursday, 16th July 1992

Conference Room, Bldg. 990 (6th Floor)

Time: 10:30 AM

POC: Dr. Promode R. Bandyopadhyay (Code 804; x2588)

Gosman + Ahmed (1987)

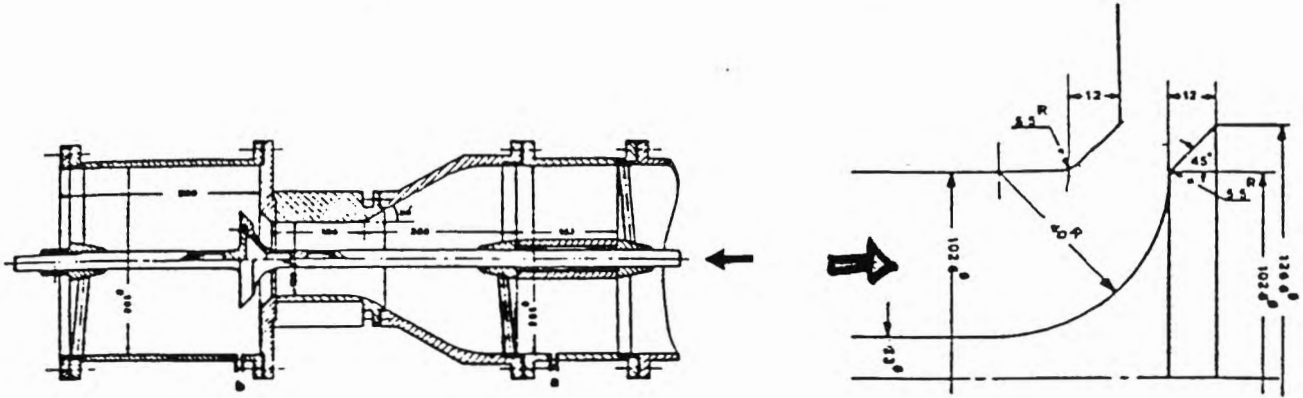


Fig 1(a) Details of the test section

Fig 1(b) Details of the valve/port assembly

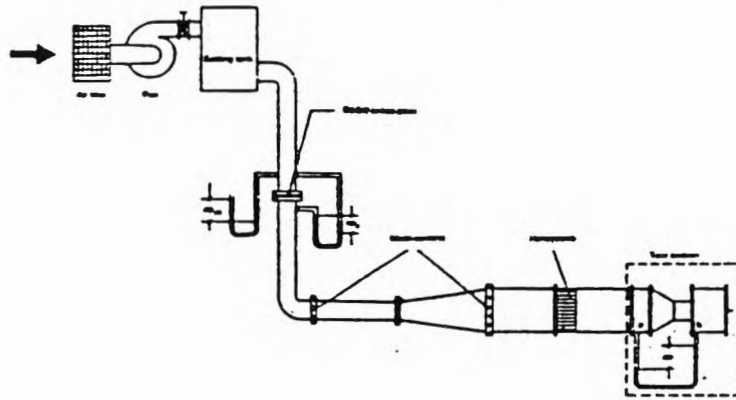


Fig 2 Schematic layout of the test rig

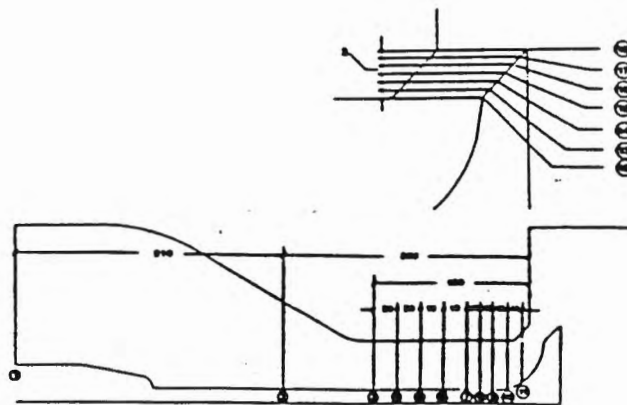
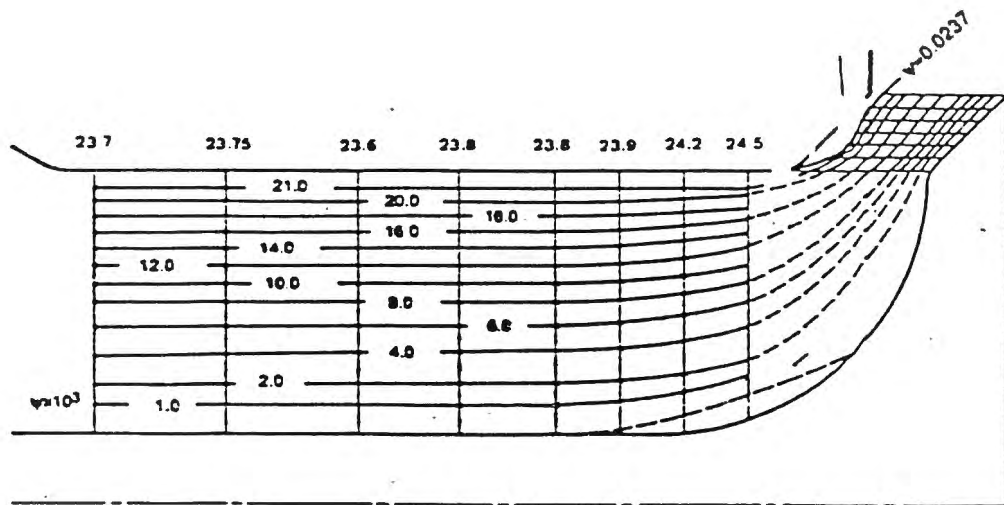


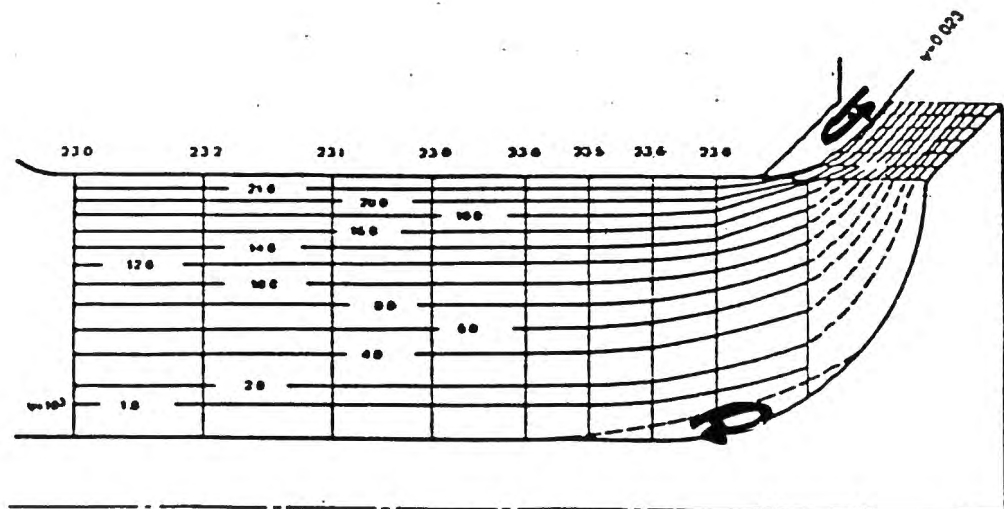
Fig 3 Locations of measuring traverses

Gosman + Ahmed (1987)

Flow Visualization



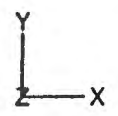
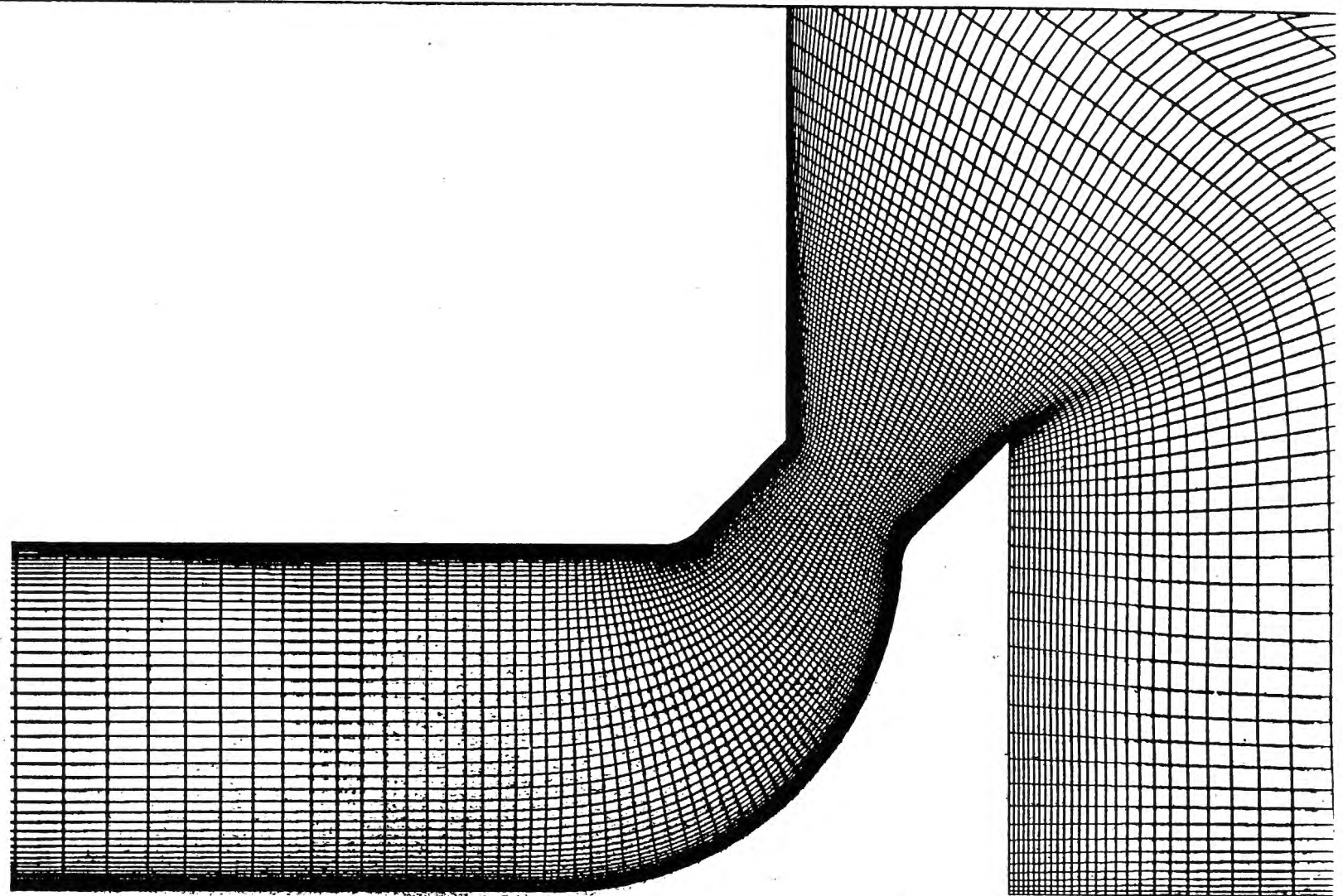
(d) $L^* = 0.20$



(e) $L^* = 0.25$

Fig 7 (concluded)

GO
000



Turbulent flow in a valve-port geometry
Grid

05/28/92
Fluent 4.1
Fluent Inc

Gosman + Ahmed (1987)

Standard k-E model calculations

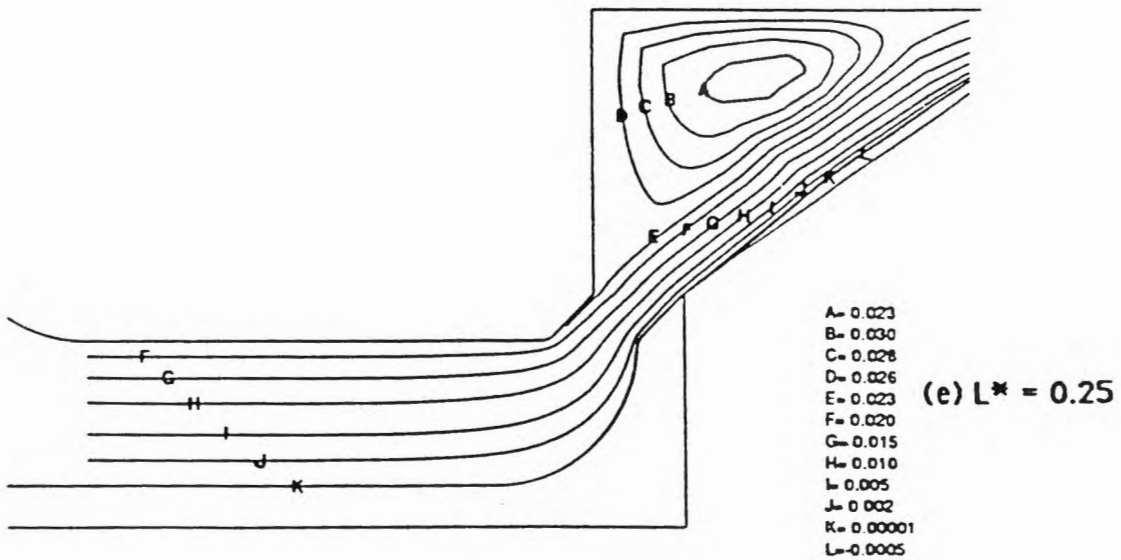
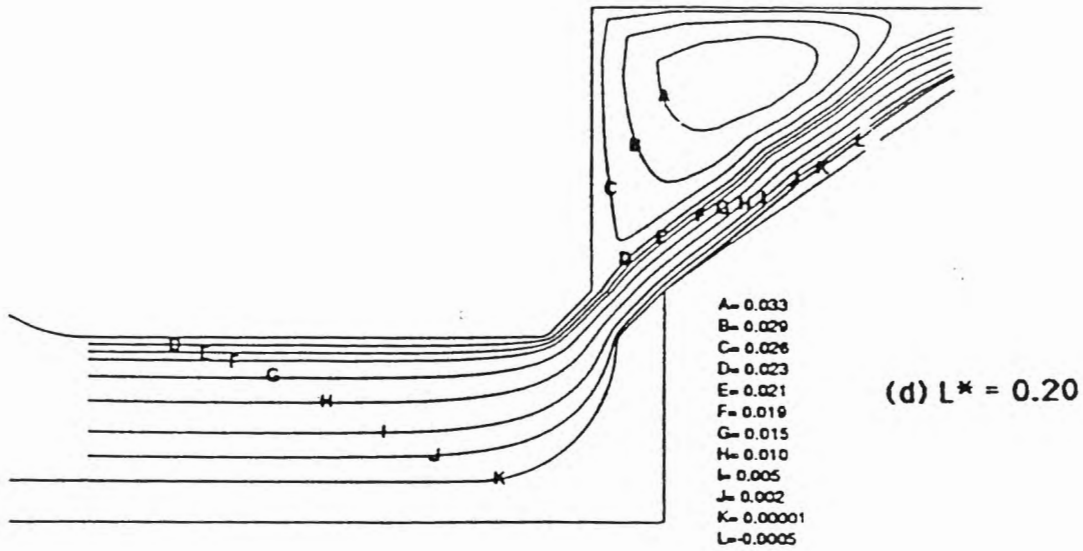


Fig 9 (concluded)

1.75E+00
1.69E+00
1.63E+00
1.57E+00
1.51E+00
1.45E+00
1.39E+00
1.33E+00
1.27E+00
1.21E+00
1.15E+00
1.09E+00
1.03E+00
9.67E-01
9.06E-01
8.46E-01
7.85E-01
7.25E-01
6.65E-01
6.04E-01
5.44E-01
4.84E-01
4.24E-01
3.64E-01
3.04E-01
2.44E-01
1.84E-01
1.24E-01
6.04E-02
2.08E-16

2-9

Turbulent flow in a valve port geometry

Velocity Vectors (Meters/Sec)

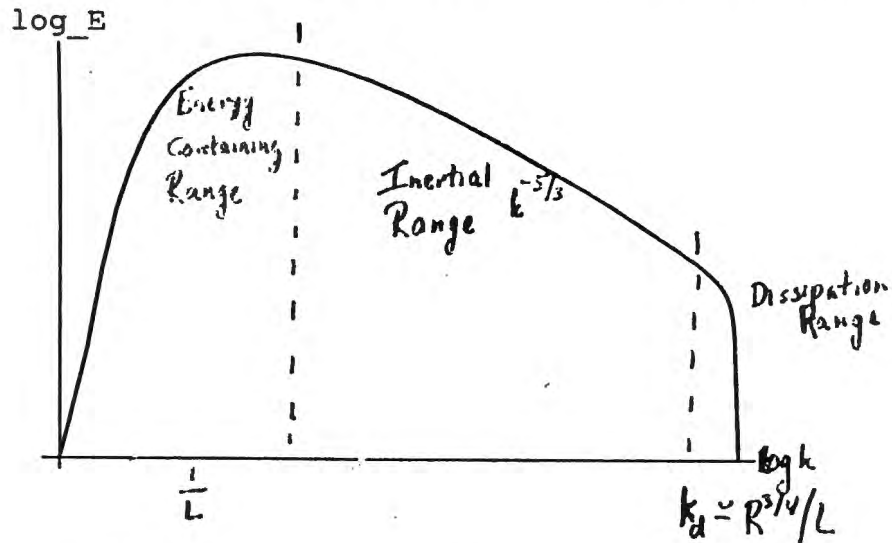
Max = 1.752E+00 Min = 0.000E+00 Time = 0.073E+00

05/28/92

Front 4.11

Front Inc.

WORK REQUIREMENTS FOR TURBULENCE COMPUTATIONS



Three-Dimensional Turbulence —

Storage $O[(R^{3/4})^3] = O[R^{9/4}]$

Work $O[(R^{3/4})^4] = O[R^3]$

Two-Dimensional "Turbulence" —

Storage $O[(R^{1/2})^2] = O[R]$

Work $O[(R^{1/2})^3] = O[R^{3/2}]$

GOAL OF TURBULENCE THEORY:

REDUCE THESE STORAGE AND WORK REQUIREMENTS

DIRECT NUMERICAL SIMULATION

DNS



Δ
Grid
size

\ll

$l_d \approx \frac{1}{Re^{3/4}} L$
Dissipation
scale

L
Large Scale
(eddy)



Navier-Stokes Equations

CM2 Simulation of Homogeneous Turbulence

-Advanced Computing Laboratory-

-Los Alamos National Laboratory-

Shiyi Chen, Xiaowen Shan

LANL

Robert Kraichnan

Zhen-Su She, Steven Orszag

Princeton

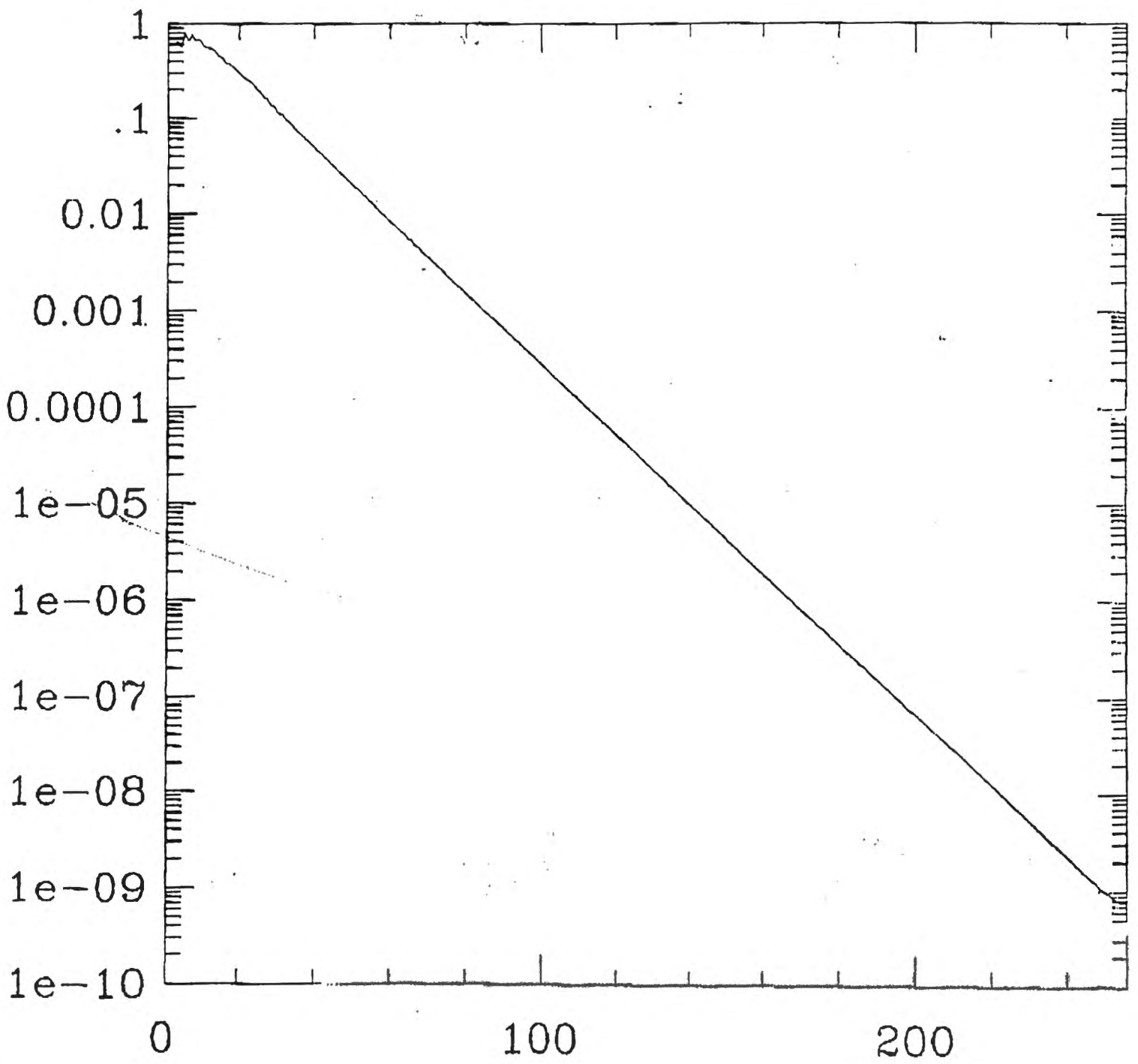
512 × 512 × 512 Spectral Code ($\approx 1+$ min/timestep)

Runs to date (11/24/91): $R_\lambda = 36, 70, 160$

$$\frac{E(k)}{k^{-5/3} [1 + \beta(k/k_d)^{4/3}]}$$

plot : lin - log

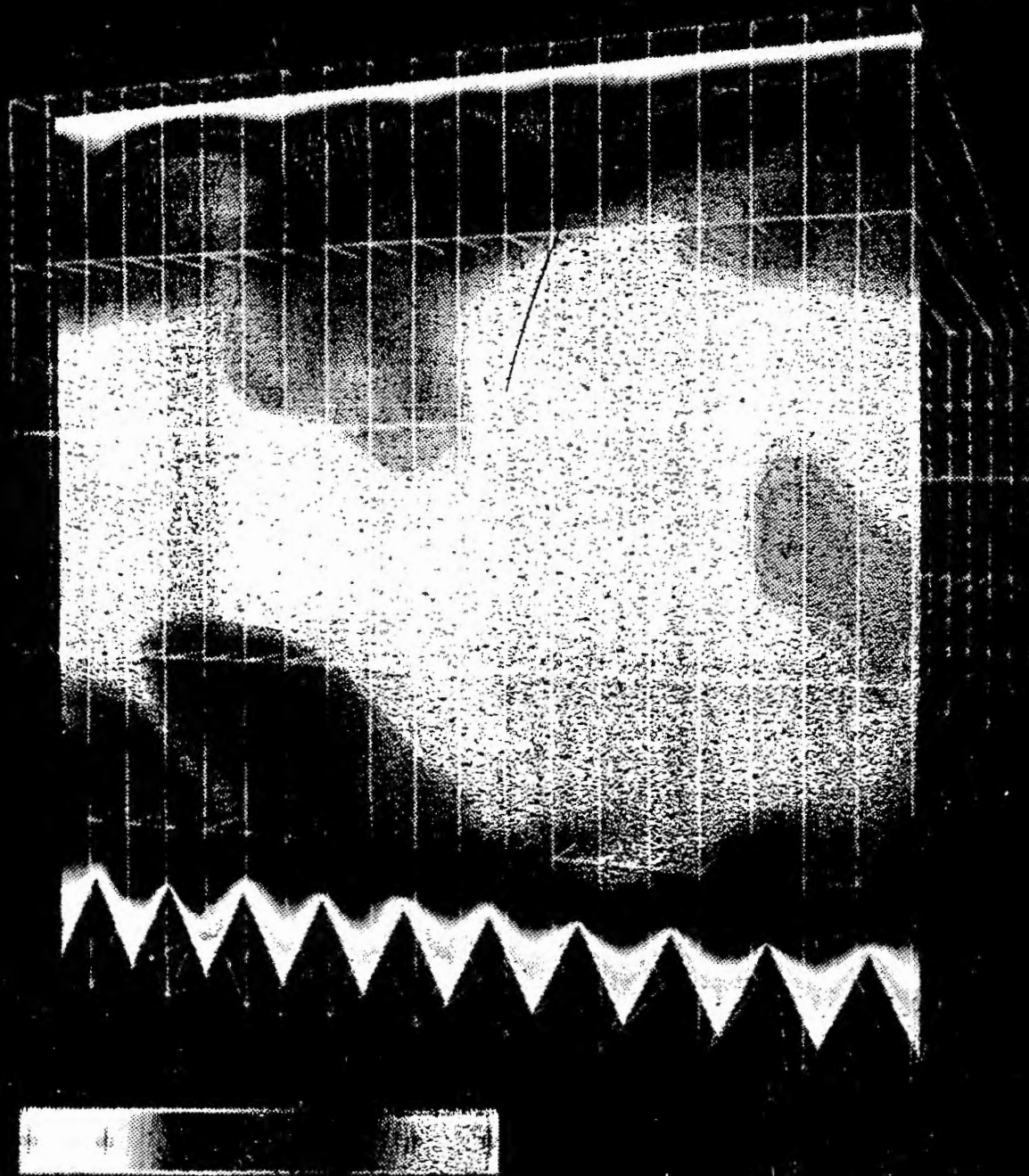
$$\beta = 0.4$$



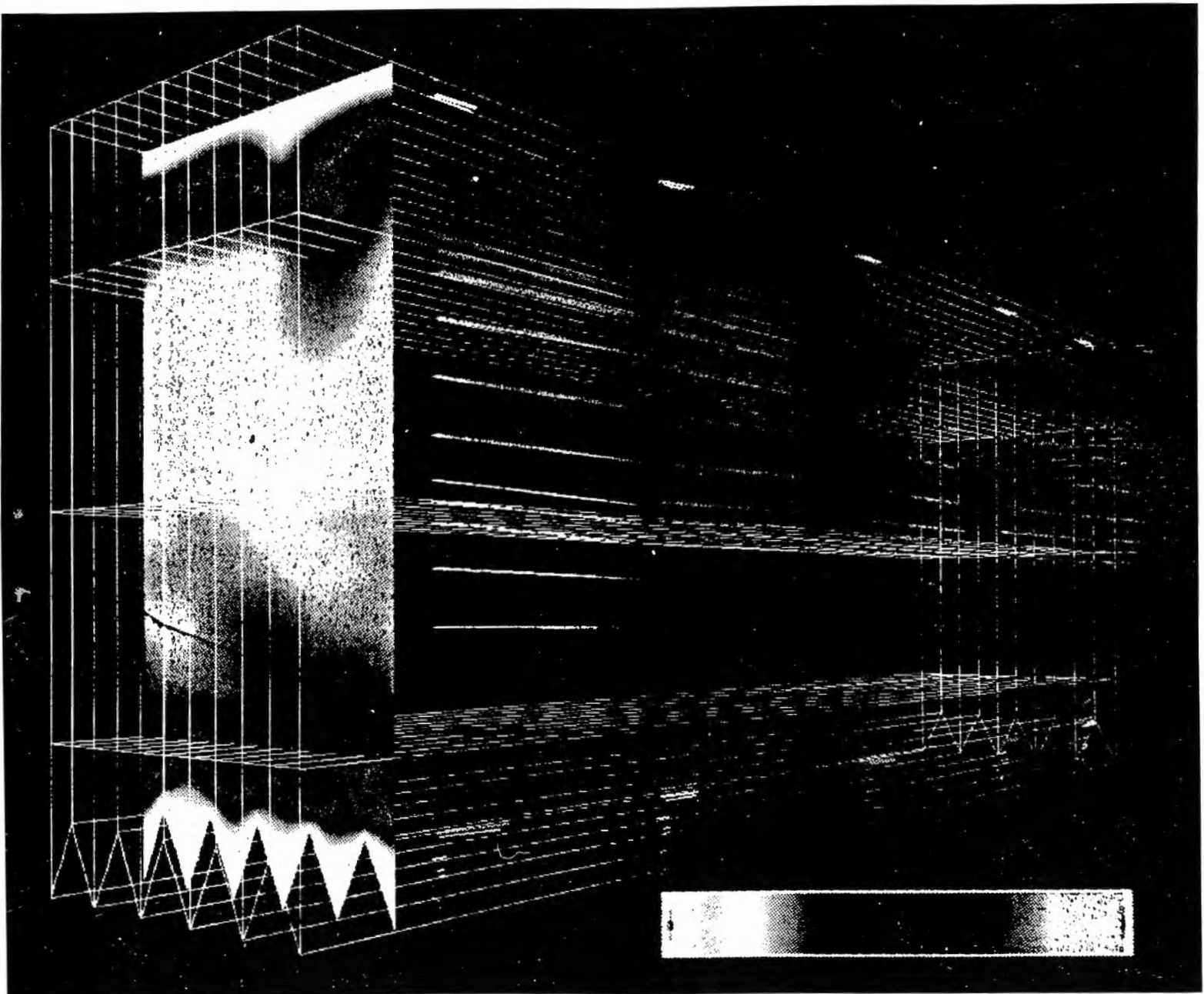
**DNS of
Turbulent
Flow Over
Riblets**

Re - 3500

**Streamwise
Velocity
Contours**



2-14



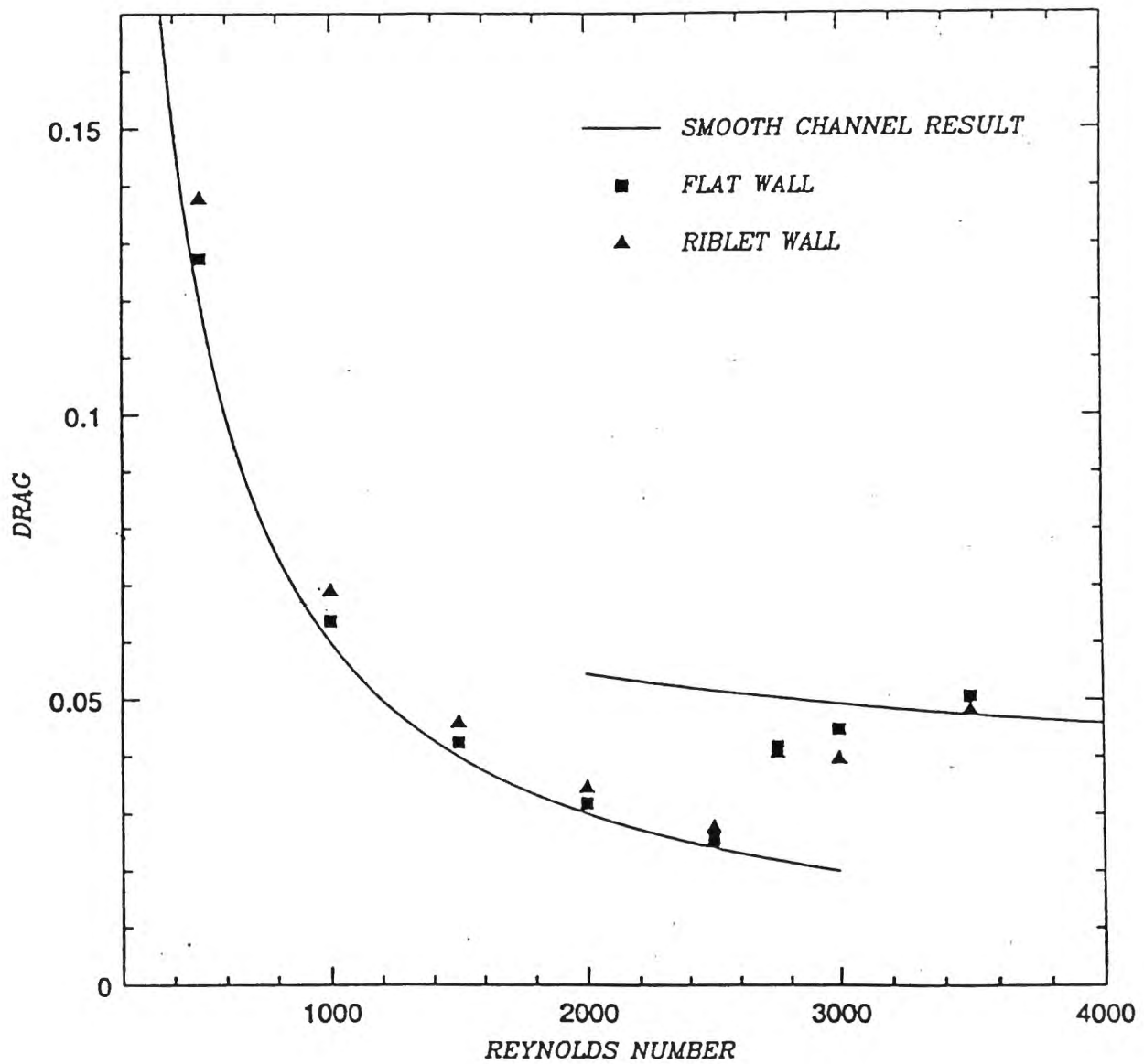


Figure 52: Drag on each wall vs. Reynolds number for riblet channel simulation.

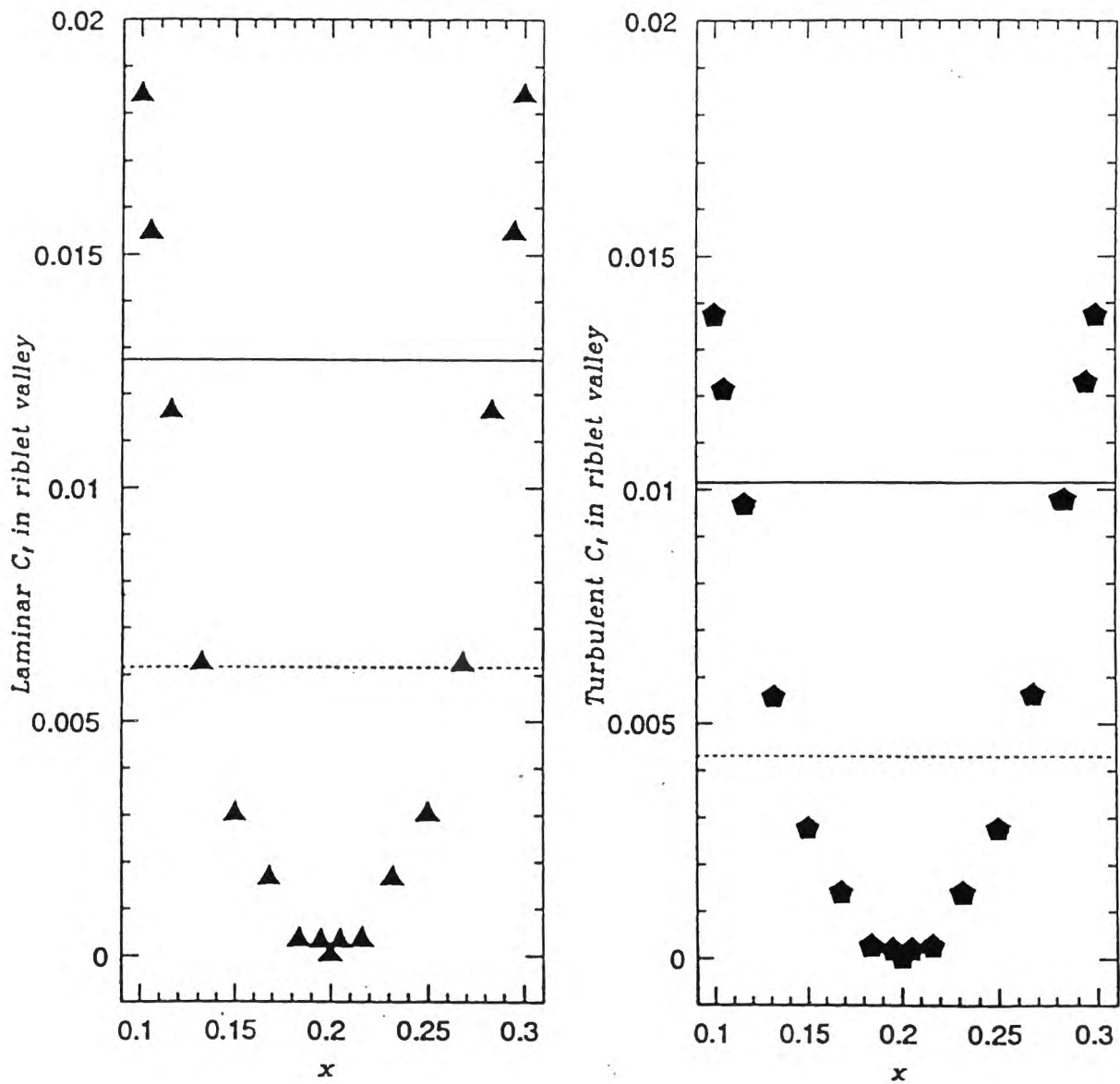
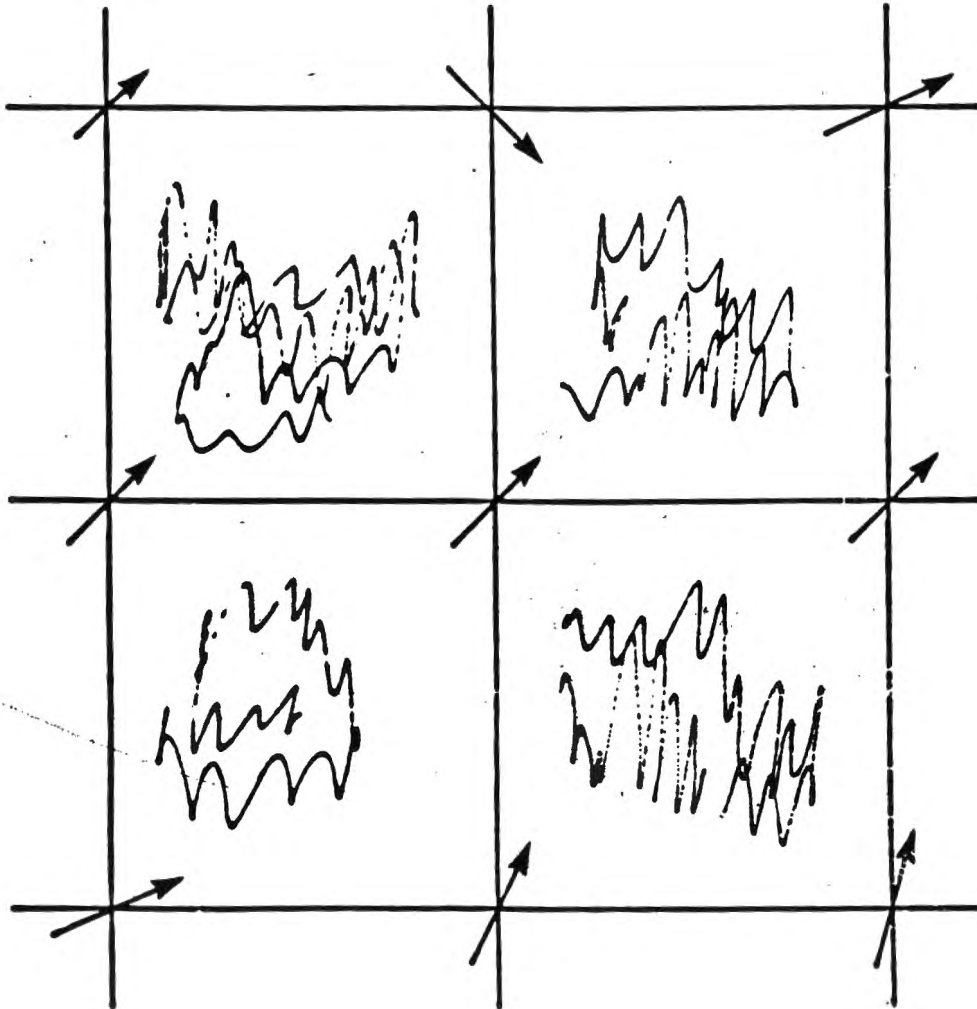


Figure 51: Comparison of laminar and turbulent local skin friction distribution inside triangular riblet valley ($Re = 1000, 3500$). Symbols and lines are described in the text.

SUBGRID TURBULENCE

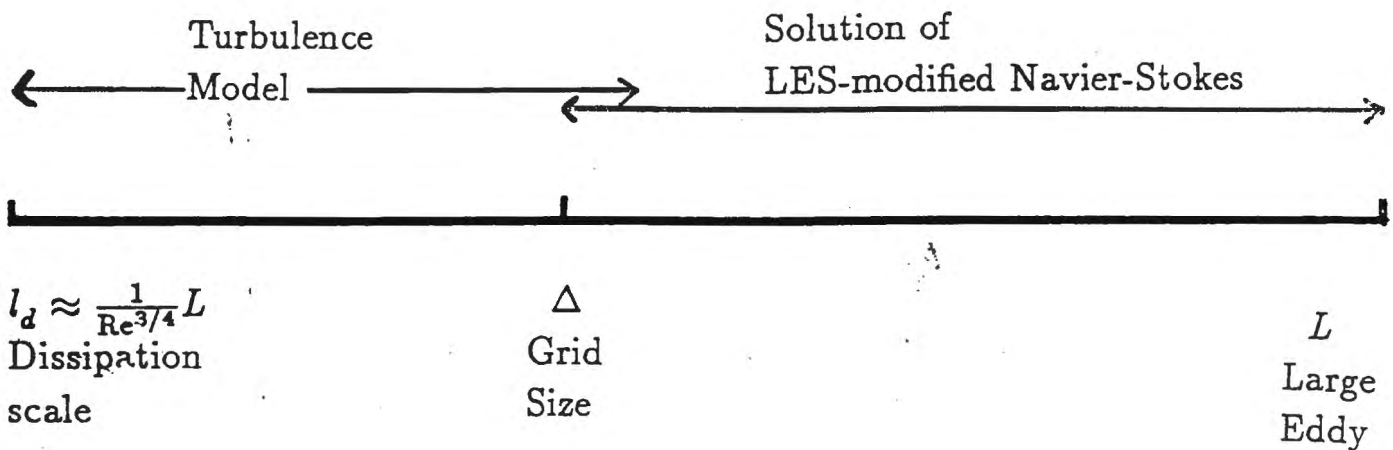


Effects of Subgrid Turbulence

- Turbulence Dissipation
- Turbulence Production -
Random Forcing

LARGE-EDDY SIMULATION

LES



Length-scale model
for 'subgrid' stresses

$$\nu_{\Delta} |\nabla U_{\text{supergrid}}|$$

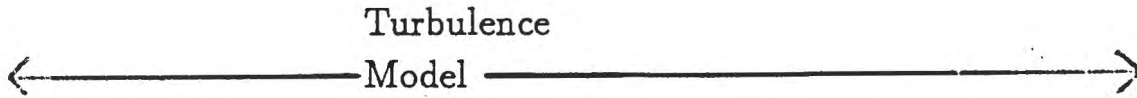
Result: $U_{\text{supergrid}}$ random on scales $\gtrsim \Delta$
large eddy

LARGE EDDY MODELS OF TURBULENCE

- Navier-Stokes Equations Solved at Large (Super-Grid) Scales
- One-Point (Eddy Viscosity, $K-\epsilon$ Model) Closure for Sub-Grid Scales
- Only Sub-Grid Small Scales Removed from the Dynamical Equations
- Large Numerical Calculations Involved Solving for Super-Grid Scales
- Applications to Homogeneous and Shear Flows
- Large Scale Structures are Computable in Detail
- Spectra are Computable Up to Grid-Induced Cutoff

TRANSPORT MODEL

REYNOLDS AVERAGED NAVIER-STOKES



$l_d \approx \frac{1}{Re^{3/4}} L$
Dissipation
scale

\ll

Δ
Grid
Size

\ll

L
Large scale
(eddy)

Eddy viscosity or $K - \mathcal{E}$ model

e.g., $\overline{u'v'} = -\nu_{\text{eddy}} \nabla \overline{U}$



Large eddies solved
by Reynolds averaged
Navier-Stokes,

e.g., $\frac{\partial \overline{U}}{\partial t} = \frac{\partial}{\partial z} (\nu + \nu_{\text{eddy}}) \frac{\partial \overline{U}}{\partial z}$

Result: Smooth, non-random \overline{U}

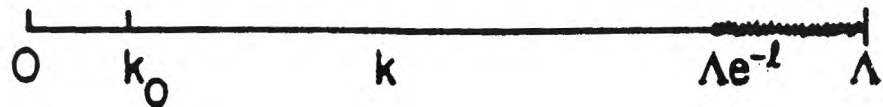
TRANSPORT MODELS OF TURBULENCE

- Reynolds Averaged Equations of Motion
- Equations for Mean Velocity, RMS Velocity Fluctuations,
 $\bar{U}(x,t)$ $\langle v(x,t) v(x,t) \rangle$
- Closures Often Based on Gradient Transport Ideas (Eddy Viscosity)
- All Small Scales Removed from the Dynamical Equations
- Applications to Shear Flows
- No Information Deduced About Small Scale Spectra, ...

ANALYTICAL THEORIES OF TURBULENCE

- Multi-Point, Multi-Time Moments Usually Involved
- All Scales Treated Statistically
- Renormalized Perturbation Methods Normally Used
- Currently Applied Principally to Homogeneous Turbulence
- Huge Numerical Calculations Involved for Shear Flows

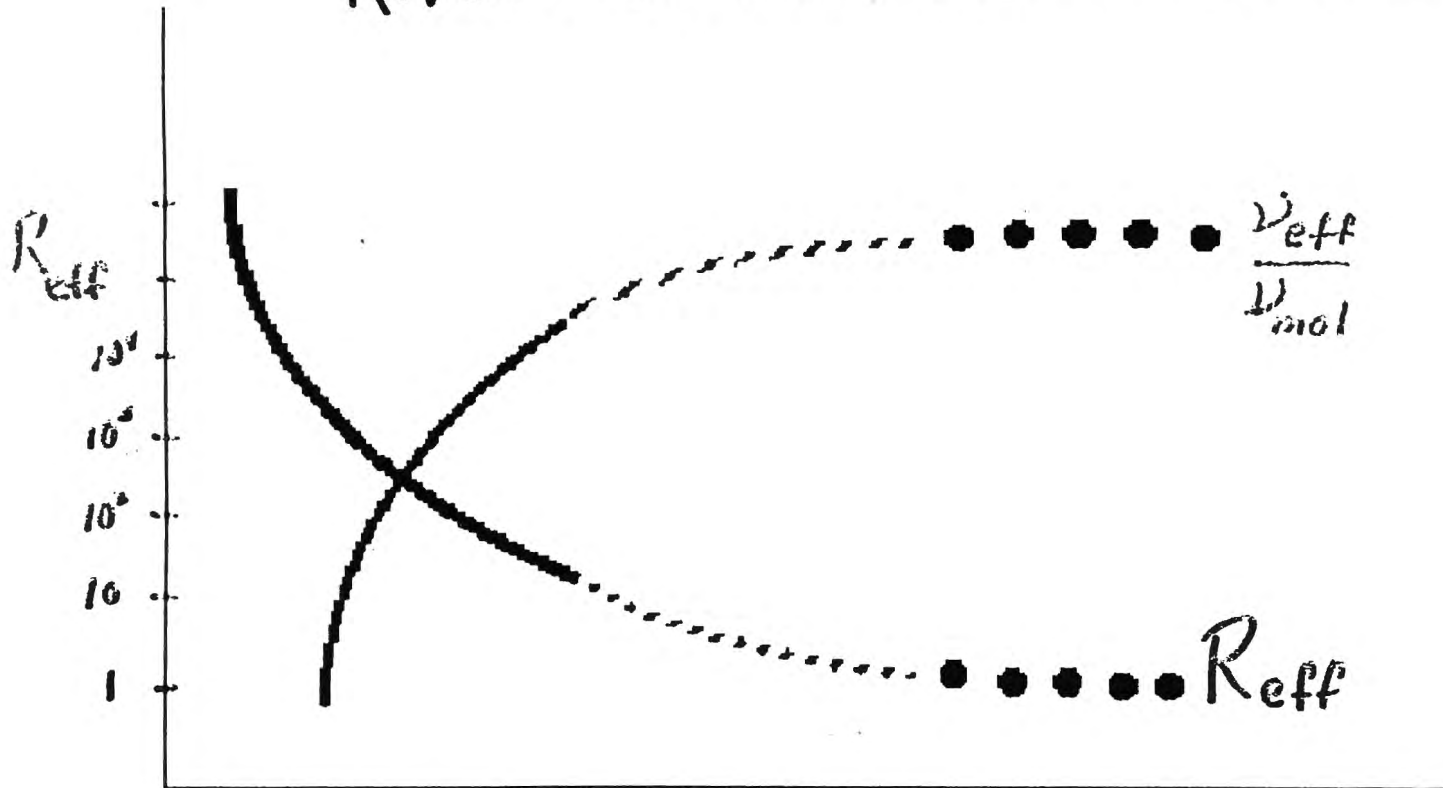
DYNAMIC RENORMALIZATION GROUP



Infrared renormalization group— long-distance behavior

1. Remove degrees of freedom
 $\Lambda e^{-l} < q < \Lambda$
2. Rewrite (by rescaling) Navier-Stokes equations as renormalized system for $v^<$ ($k < \Lambda e^{-l}$) with modified viscosity, force, coupling

RNG: Schematic of Mode Elimination Procedure



“The renormalization group is one of the fundamental approaches to tackling this problem of what to do when you cannot make your grid small enough to use the fundamental equation. How do you increase the grid spacing beyond the level of a straight numerical approach, yet preserve all of the reliability that working from a fundamental equation can give you?”

Kenneth Wilson (1985)

Intrinsic Stirring Force in Turbulence and the ε -Expansion

Large-scale force to model the effects of *initial* and *boundary* conditions

$$(-i\omega + \nu_0 k^2)u_\alpha(\mathbf{k}, t) = -\frac{1}{2}iP_{\alpha\beta\gamma}(\mathbf{k}) \int u_\beta(\mathbf{p}, \Omega)u_\gamma(\mathbf{k} - \mathbf{p}, \omega - \Omega) d\mathbf{p}d\Omega + f_\alpha(\mathbf{k}, \omega)$$

$$\langle f_\alpha(\hat{\mathbf{k}})f_\beta(\hat{\mathbf{k}}') \rangle \propto D_0 P_{\alpha\beta}(\mathbf{k})\delta(\mathbf{k})\delta(\mathbf{k} + \mathbf{k}')\delta(\omega + \omega')$$

DIFFICULTY: Nonlinear solutions of the Navier-Stokes equations involve an 'infinity' of interacting f 's to produce $u(\mathbf{k})$ [\mathbf{k} finite]

2-27

Correspondence Principle (Yakhot & Orszag 1986)

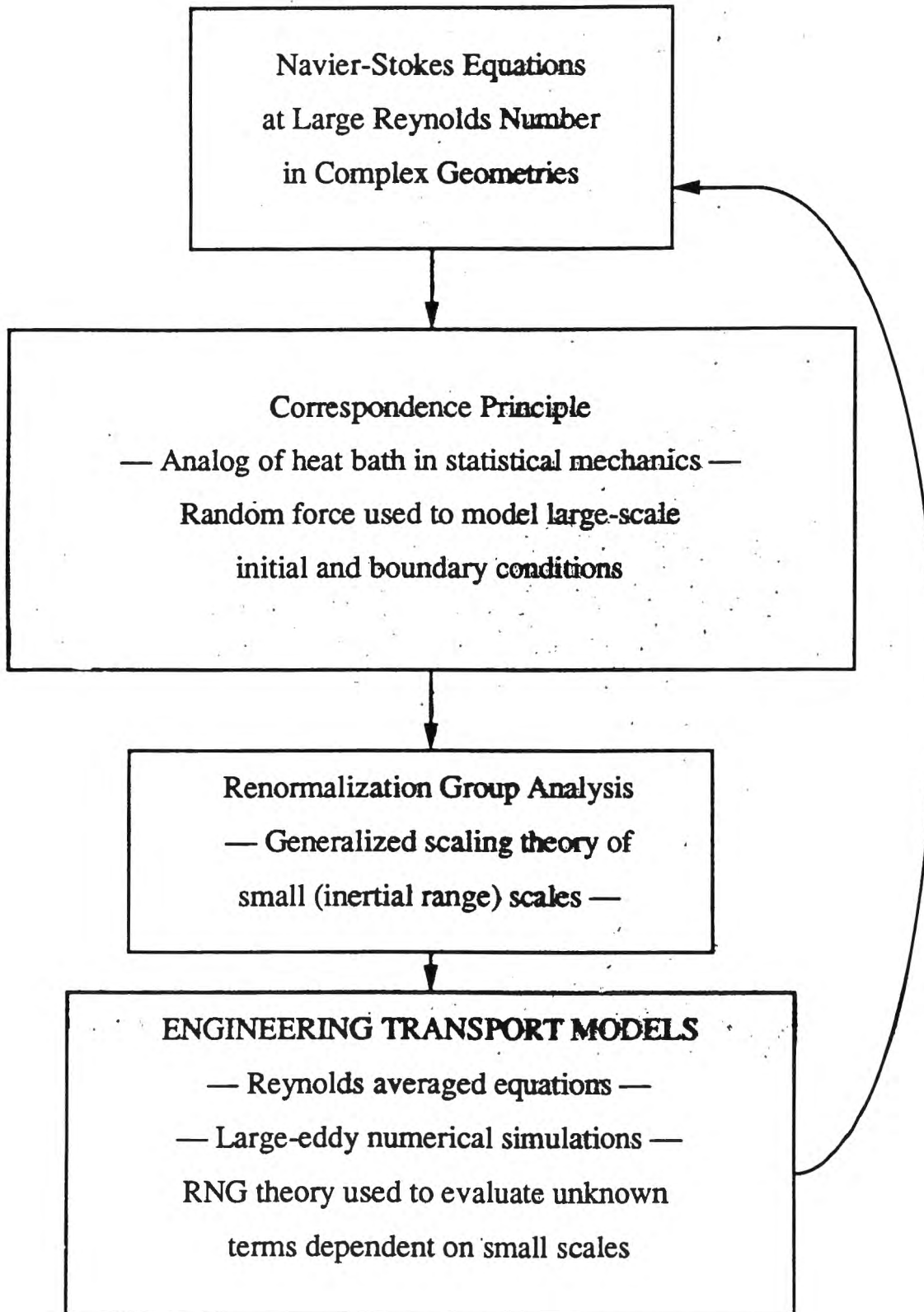
$$\langle f_\alpha(\hat{\mathbf{k}})f_\beta(\hat{\mathbf{k}}') \rangle \propto D_1 P_{\alpha\beta}(\mathbf{k})k^{1-\varepsilon}\delta(\mathbf{k} + \mathbf{k}')\delta(\omega + \omega')$$

$$\delta(\mathbf{k}) = \lim_{\varepsilon \rightarrow 4} \frac{(4 - \varepsilon)k^{1-\varepsilon}}{4\pi}$$

Gel'fand

RENORMALIZATION GROUP (RNG) THEORY

— A Practical Approach to the Turbulence Problem —



Langevin Model

$$\frac{\partial u^\ell}{\partial t} = -\nu(\ell) u^\ell \ell^{-2} + f^\ell$$

Nonlocal convolution operator

Assume

$$\frac{d\nu(\ell)}{d\ell} \propto \mathcal{E} \quad (\text{rate of energy dissipation})$$

Dimensional analysis \implies

$$\frac{d\nu}{d\ell} = \frac{A\mathcal{E}\ell^3}{\nu^2}, \quad \nu(\ell_d) = \nu_0$$

Solution:

$$\nu(\ell) = \nu_0 \left[1 + \frac{3}{4} \frac{A\mathcal{E}}{\nu_0^3} \left(\ell^4 - \ell_d^4 \right) \right]^{1/3} \quad (\ell > \ell_d)$$

$$\nu(\ell) \sim \left(\frac{3}{4} A\mathcal{E} \right)^{1/3} \ell^{4/3} \quad (\ell \gg \ell_d)$$

Renormalization Group Subgrid Model for LES

$$K \propto 1/\Delta$$

$$\nu_{eddy} = \nu_{mol} \left[1 + \frac{3}{4} \frac{A\mathcal{E}}{(2\pi)^4 \nu_{mol}^3} (\Delta^4 - \eta_d^4) \right]^{1/3}$$

$$\mathcal{E} = \nu_{eddy} |\nabla \bar{U}|^2$$

High turbulence limit

$$\nu_{eddy} \sim \left[\frac{3}{4} \frac{A}{(2\pi)^4} \right]^{1/2} \Delta^2 |\nabla \bar{U}|$$

Transitional regimes

$$\nu_{eddy}^3 = \nu_{mol}^3 + \frac{3}{4} \frac{A}{(2\pi)^4} (\Delta^4 - \eta_d^4) \nu_{eddy} |\nabla \bar{U}|^2$$

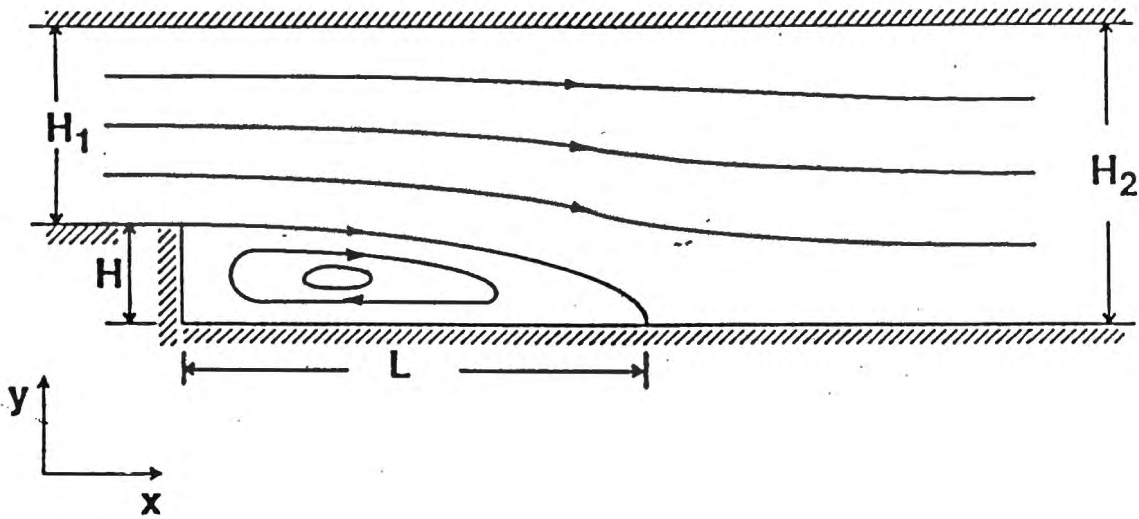
— unphysical roots can be a problem

Alternate Formulation

$$\mathcal{E} = \frac{S^2}{\nu_{eddy}} \quad S = \nu_{eddy} |\nabla \bar{U}|$$

$$\nu_{eddy}^4 = \nu_{mol}^3 \nu_{eddy} + \underbrace{\frac{3}{4} \frac{AS^2}{(2\pi)^4} (\Delta^4 - \eta_d^4)}_{\geq 0}$$

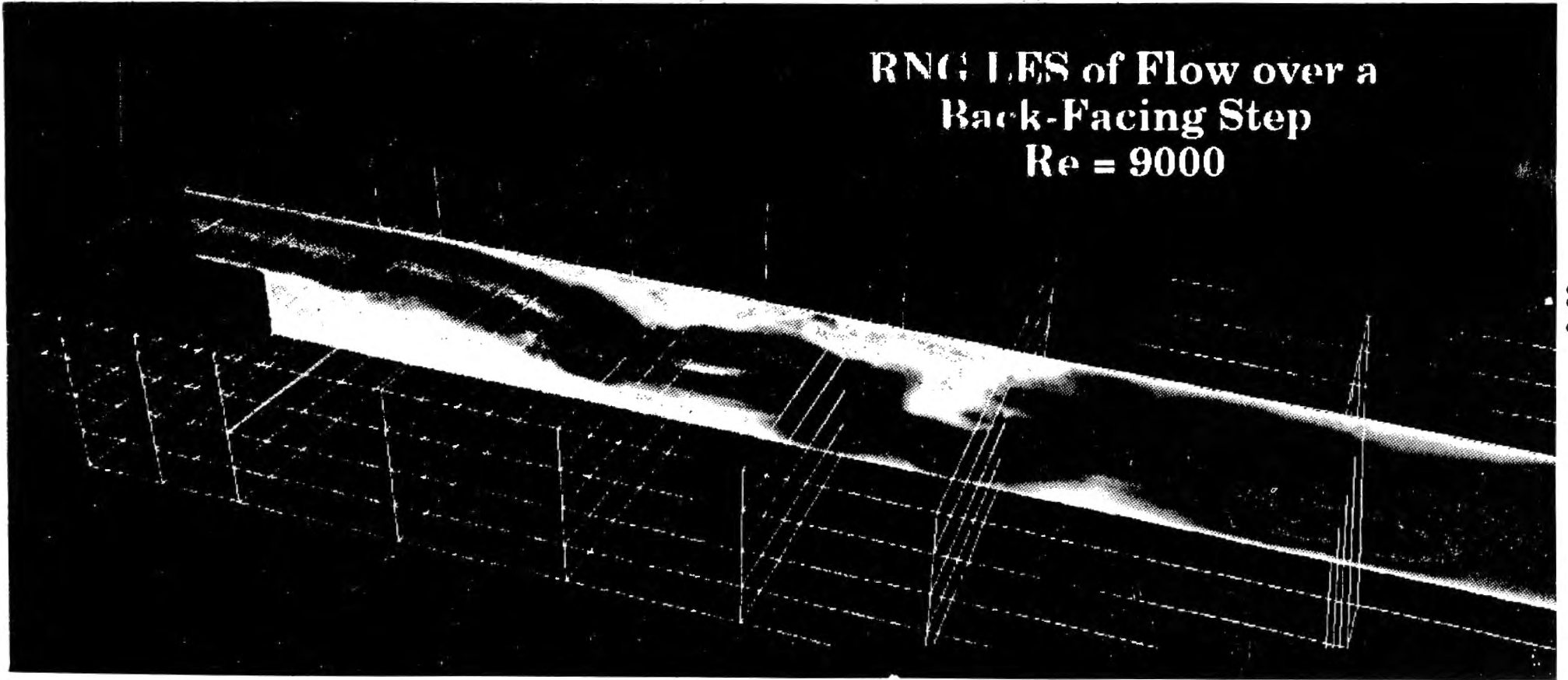
Only 1 real root with $\nu_{eddy} \geq \nu_{mol}$



Turbulent flow over a backward facing step

Figure 3

**RNG LES of Flow over a
Back-Facing Step
 $Re = 9000$**



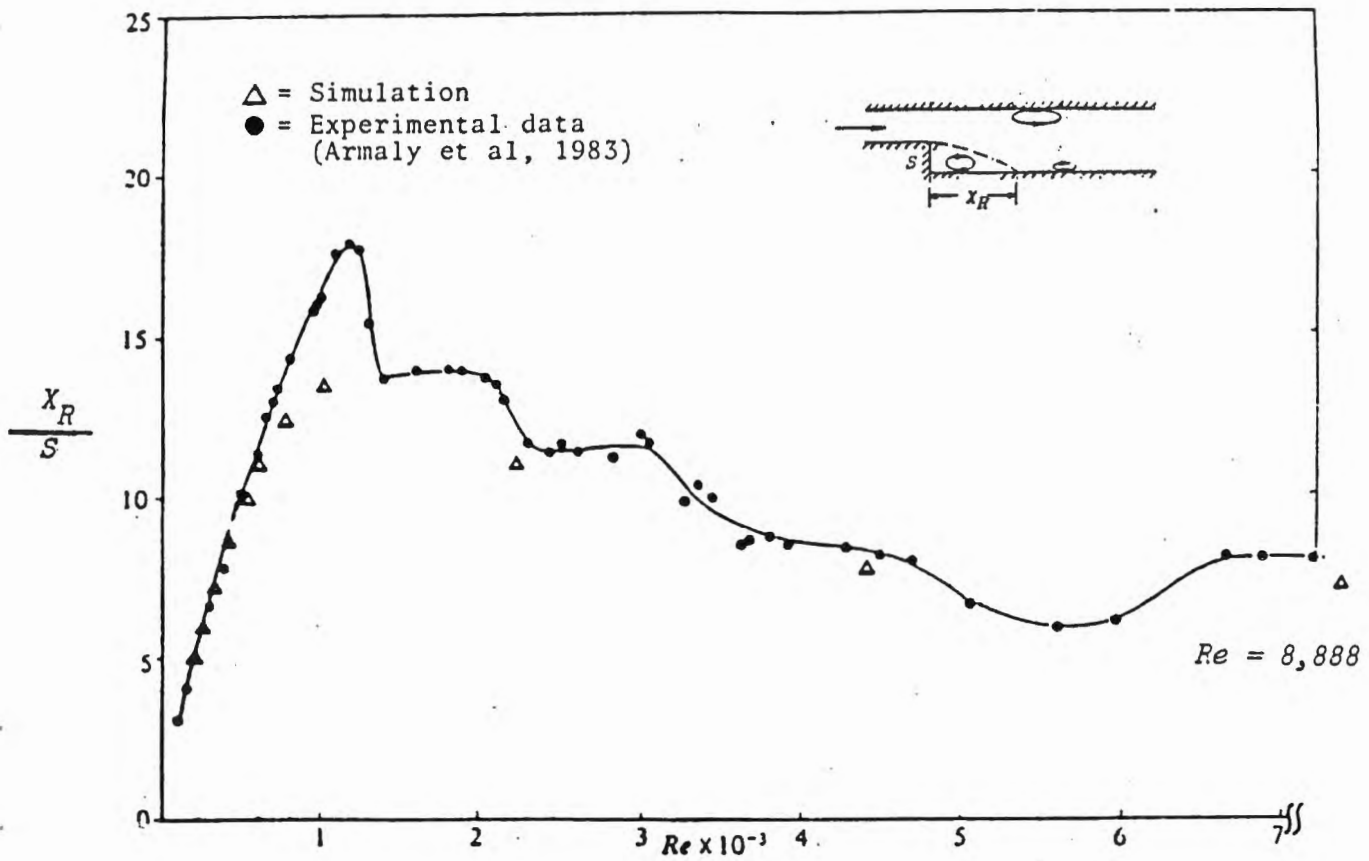


Figure 9: Normalized separation length X_R versus Reynolds number; S = step height.

APPLICATION OF RG TO TURBULENCE MODELLING

Prandtl mixing length theory

$$\mathcal{E} = \nu_{eddy} |\nabla \bar{U}|^2$$

$$k_0 = 2\pi/L$$

$$\nu_{eddy} \sim \left(\frac{3}{4}A\right)^{1/3} \mathcal{E}^{1/3} k_0^{-4/3}$$

$$\nu_{eddy} = \left[\underbrace{\left\{ \left(\frac{3}{4}A\right)^{1/4} / 2\pi \right\} L}_{= 0.094} \right]^2 |\nabla \bar{U}|$$

RNG-BASED ALGEBRAIC MODEL

Eddy Viscosity:

$$\nu = \nu_0 \left(1 + H \left(\frac{a \Delta^4}{\nu_0^3} \bar{\epsilon} - C \right) \right)^{1/3}, \quad (1)$$

$$\bar{\epsilon} = \nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)^2 + \beta U_i \frac{\partial p}{\partial x_i} \quad (2)$$

Length Scale (Δ):

$$\Delta = y_+ \text{ if } y_+ < \lambda, \text{ and } = \lambda \text{ otherwise,} \quad (3)$$

where

$$\lambda = \gamma \left(1 - \frac{\theta}{\delta_*} \right)^{-1} \delta_* \quad (4)$$

δ_* - displacement thickness
 θ - momentum-loss thickness
 δ_*/θ - shape factor

Pressure Gradient Term ($\beta U_i \partial p / \partial x_i$):

$$\beta = \beta_1 (1 - \exp(-\beta_2 (y_+ - \Delta) / \lambda)) \quad (5)$$

Constants:

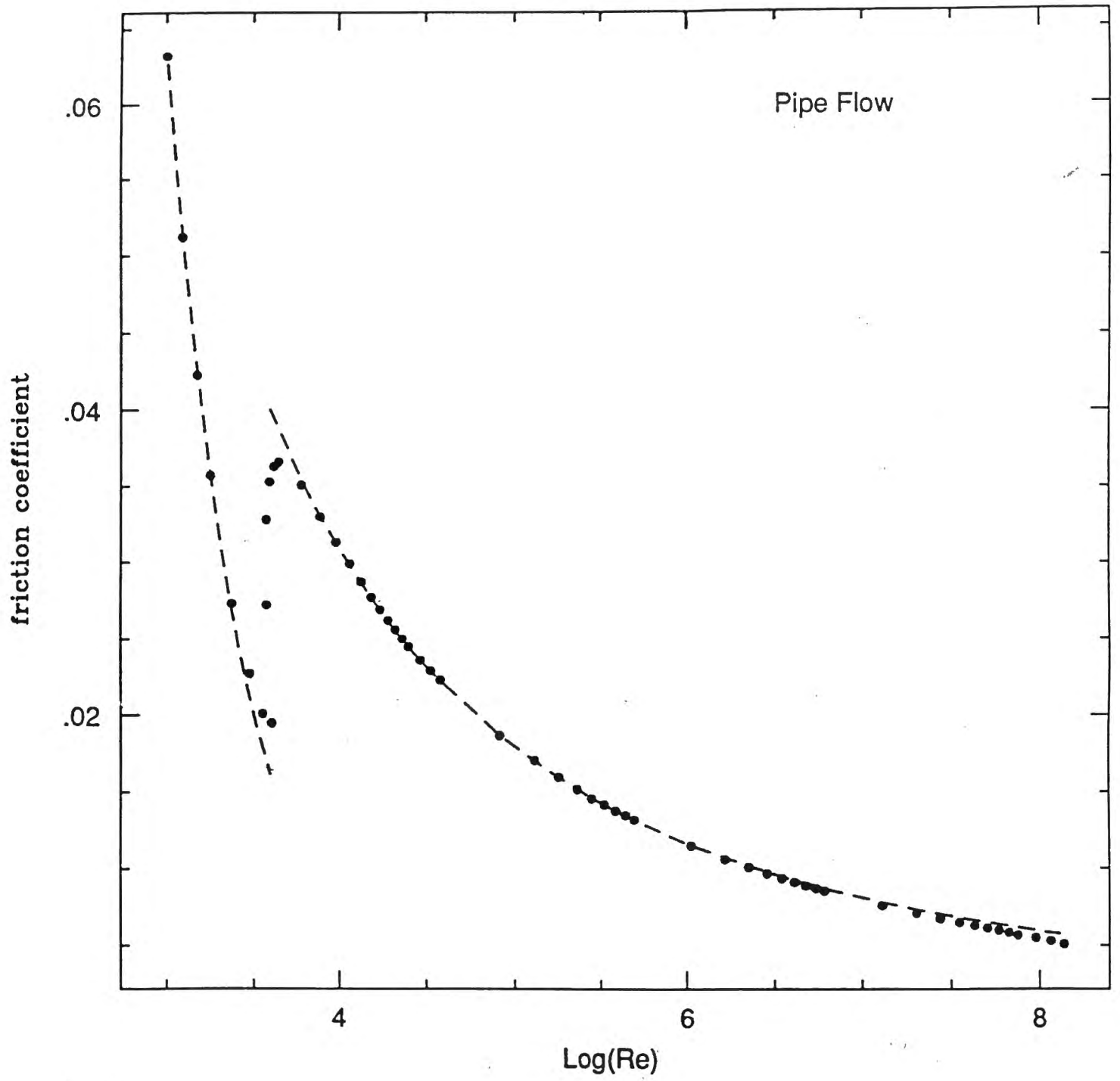
$$a = 0.0256$$

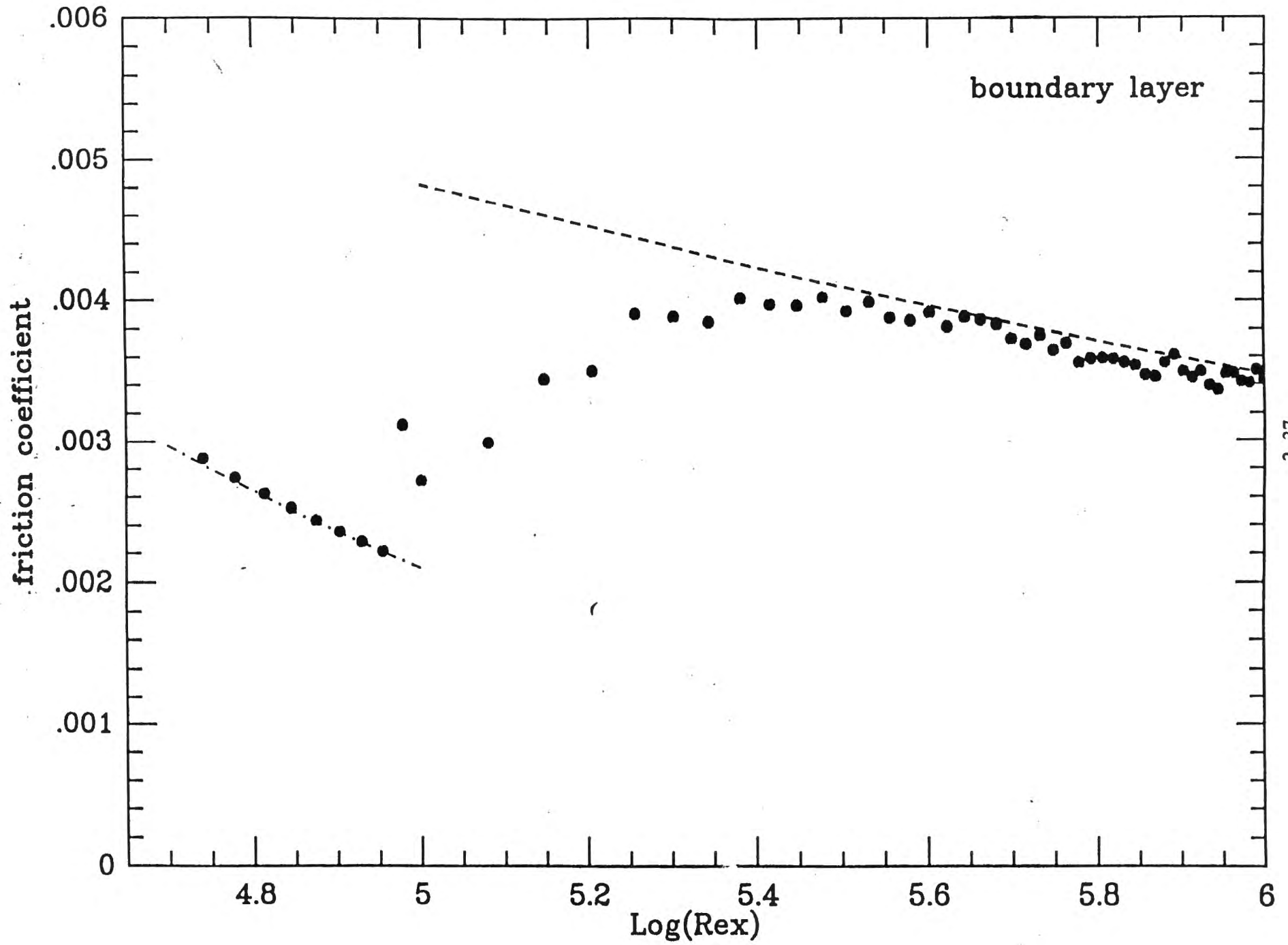
$$C \approx 100$$

$$\gamma = 0.28$$

$$\beta_1 = 5.$$

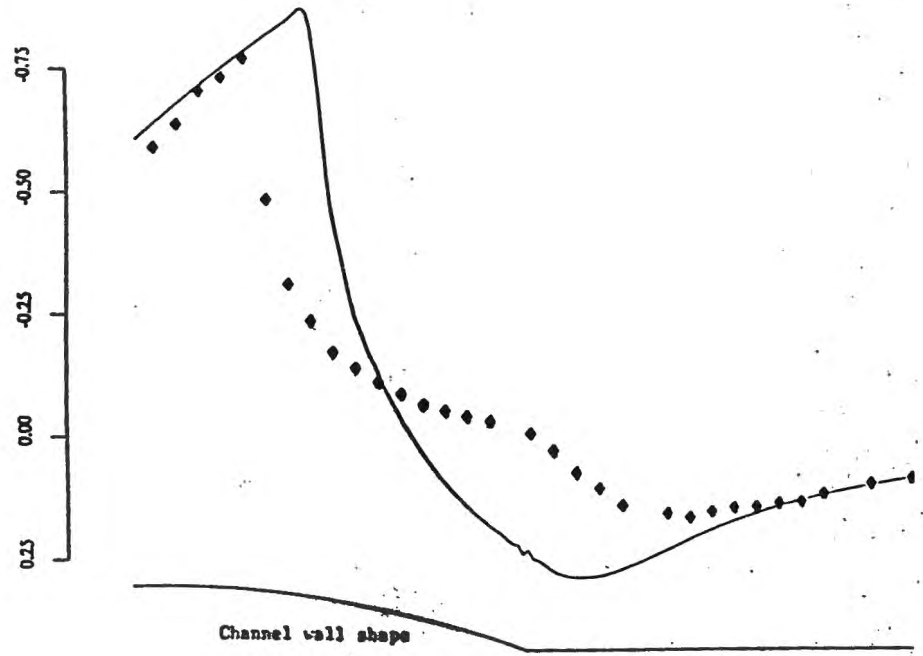
$$\beta_2 = 0.12$$





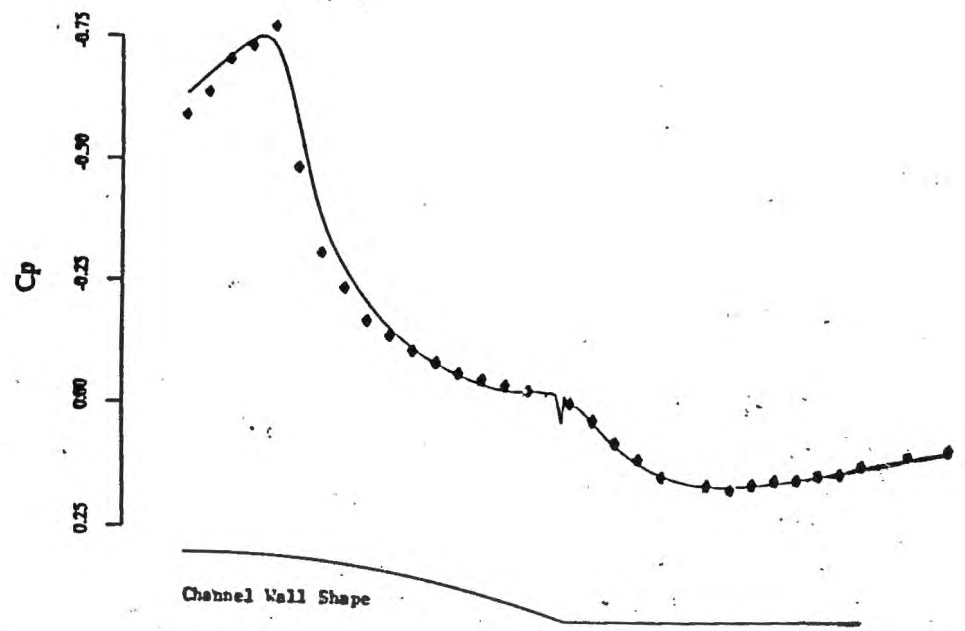
88-2

◆ Experiments
 — Computation
 Baldwin-Lomax Model



ARC BAL & LOMAX
 MACH 0.875 ALPHA 0.000
 CL -0.0901 CD 0.0156 CM 0.4685
 GRID 320X64 NCYC 200 RES0.000E+00

◆ Experiments
 — Computation
 RNG Algebraic Model



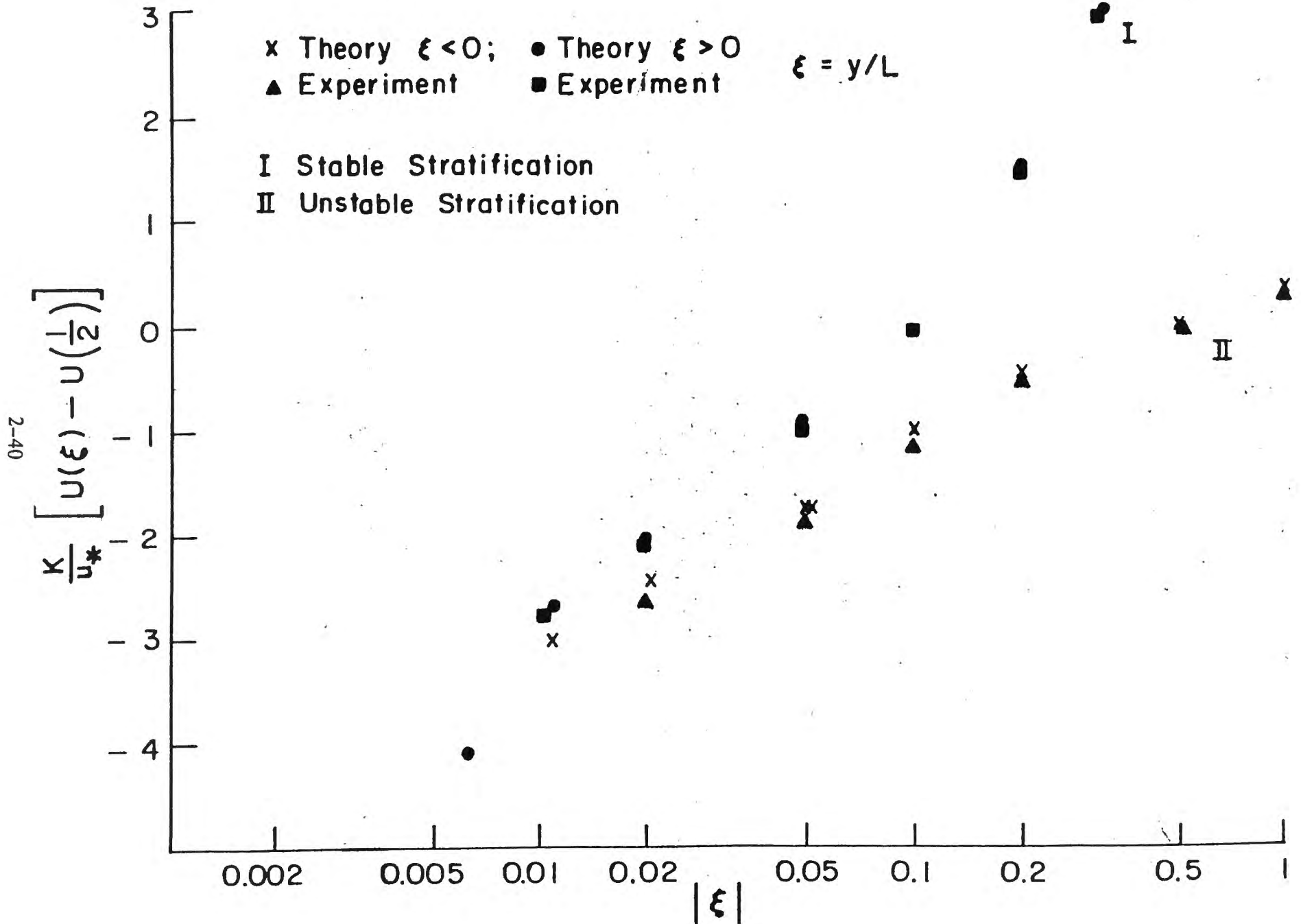
ARC
 MACH 0.875 ALPHA 0.000
 CL -0.0241 CD 0.0162 CM 0.1344
 GRID 320X64 NCYC 100 RES0.000E+00

Additional Physics

Example: Stratified Shear Flow

$$\nu_{eddy} = \nu_0 \left[1 + \frac{3}{4} \frac{A}{\nu_0^3} \left(\mathcal{E} - g \frac{\partial \bar{T}}{\partial z} \right) (\ell^4 - \ell_d^4) \right]^{1/3}$$

RNG CLOSURE FOR STRATIFIED TURBULENCE



APPLICATION OF RG TO TURBULENCE MODELLING

RG Length Scale Model for High Mach Flows

$$\mathcal{K} = \frac{3}{2} \mathcal{E}^{2/3} k^{-2/3} \lesssim \gamma^2 c^2 \left[V^2 < \gamma^2 c^2 \text{ or else eddy shocklets form} \right]$$

so

$$\nu_{eddy} = \left(\frac{3}{4} A \right)^{1/3} \mathcal{E}^{1/3} k_0^{-4/3} \lesssim \frac{c^4}{\mathcal{E}} \approx \frac{c^4}{\nu_{eddy}} |\nabla \bar{U}|^2$$

so

$$\nu_{eddy} \lesssim \frac{c^2}{|\nabla \bar{U}|} \quad \left(\text{not } \nu_{eddy} \propto |\nabla \bar{U}| \text{ (Prandtl)} \right)$$

Self-Focusing of High Ma Jet/Wake Flows

RNG K- \mathcal{E} Eddy Viscosity

High Turbulence Formulation

$$\nu(\ell) \sim \left(\frac{3}{4}A\mathcal{E}\right)^{1/3} \ell^{4/3}$$

$$K = \int_{\ell^{-1}}^{\infty} C_{K0} \mathcal{E}^{2/3} k^{-5/3} dk = \frac{3}{2} C_{K0} \mathcal{E}^{2/3} \ell^{2/3}$$

$$\nu = \frac{\left(\frac{3}{4}A\right)^{1/3}}{\left(\frac{3}{2}C_{K0}\right)^2} \frac{K^2}{\mathcal{E}}$$

$$C_{\mu} = \frac{\left(\frac{3}{4}A\right)^{1/3}}{\left(\frac{3}{2}C_{K0}\right)^2} \stackrel{\text{RNG}}{=} 0.0845$$

General Foundation

$$\nu = C_{\mu} K^2 / \mathcal{E} \quad \text{only if } \nu \gg \nu_0$$

$$\nu = \nu_0 \left[1 + \sqrt{\frac{C_{\mu}}{\nu_0}} \frac{K}{\sqrt{\mathcal{E}}} \right]^2 \quad (\nu \geq \nu_0)$$

Renormalization Group (RNG) K-E Models

K = turbulent kinetic energy $K(\vec{x}, t) = \frac{3}{2} V_{rms}^2$

ϵ = turbulent dissipation $\epsilon = \nu |\nabla v|^2$

$$\frac{D\vec{U}}{Dt} = \dots$$

$$\frac{DK}{Dt} = \dots$$

$$\frac{D\epsilon}{Dt} = \dots$$

RNG Theory vs Standard Model (Empirical)

- High Reynolds # constants evaluated by theory
- Rate of strain term - important for non-equilibrium effects and rapid distortion limit
- Low Reynolds # modifications given by RNG theo.
 - No wall functions
- Boundary conditions
- Stratification & rotation effects accounted for

RNG K- ε Model with Finite Rate-of-Strain Effects

V. Yakhot, S. Thangam, T. B. Gatski,
S. A. Orszag, C. G. Speziale, L. M. Smith

$$\frac{\partial U_i}{\partial t} + \mathbf{U} \cdot \nabla U_i = -\nabla_i p + \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right]$$

$$\frac{\partial \bar{K}}{\partial t} + \mathbf{U} \cdot \nabla \bar{K} = -\bar{\varepsilon} - \bar{\tau}_{ij} S_{ij} + \frac{\partial}{\partial x_i} \left(\alpha_K \nu \frac{\partial \bar{K}}{\partial x_i} \right)$$

$$\frac{\partial \bar{\varepsilon}}{\partial t} + \mathbf{U} \cdot \nabla \bar{\varepsilon} = -C_{\varepsilon_1} \frac{\bar{\varepsilon}}{\bar{K}} \bar{\tau}_{ij} S_{ij} - C_{\varepsilon_2} \frac{\bar{\varepsilon}^2}{\bar{K}} - \mathcal{R} + \frac{\partial}{\partial x_i} \left(\alpha_{\varepsilon} \nu \frac{\partial \bar{\varepsilon}}{\partial x_i} \right)$$

$$C_{\varepsilon_1} = 1.42, \quad C_{\varepsilon_2} = 1.68, \quad C_{\mu} = 0.0845, \quad \alpha_K = \alpha_{\varepsilon} = 1.39$$

$$\mathcal{R} = 2\nu_0 S_{ij} \frac{\overline{\partial u_\ell}}{\partial x_i} \frac{\overline{\partial u_\ell}}{\partial x_j}$$

Padé Approximation to Expansion of \mathcal{R} in Powers of

$$\eta = \frac{S\bar{K}}{\bar{\varepsilon}}$$

$$\mathcal{R} = \frac{C_{\mu} \eta^3 (1 - \eta/\eta_0) \bar{\varepsilon}^2}{1 + \beta \eta^3} \frac{1}{\bar{K}}$$

Evaluation of \Re

- Consistency with weakly sheared turbulence $\eta \rightarrow 0$

$$\Re \sim \nu S^3$$

- Consistency with strongly sheared (rapid distortion) turbulence

$$\Re = O(\eta) \quad \eta \rightarrow \infty$$

Padé Approximant

$$\Re = \frac{\nu_T S^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3}$$

($\sum r_n \eta^n$ is a geometrical series)

$$\Re = \frac{C_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3} \frac{\bar{\epsilon}^2}{K}$$

RNG FORMULATION OF K-ε TURBULENCE MODEL

$$\partial \varepsilon / \partial t + U_k \partial \varepsilon / \partial x_k = a \partial U_j / \partial x_k \langle u_j u_k \rangle - Y + \partial / \partial x_k \alpha_\varepsilon \nu \partial \varepsilon / \partial x_k$$

$$\partial k / \partial t + U_k \partial k / \partial x_k = \partial U_j / \partial x_k \langle u_j u_k \rangle - \varepsilon + \partial / \partial x_k \alpha_k \nu \partial k / \partial x_k$$

$$d(a/\nu \varepsilon) = -0.2176 dv/Y_1$$

$$d(Y/\nu \varepsilon^3) = -0.3089 dv/Y_1$$

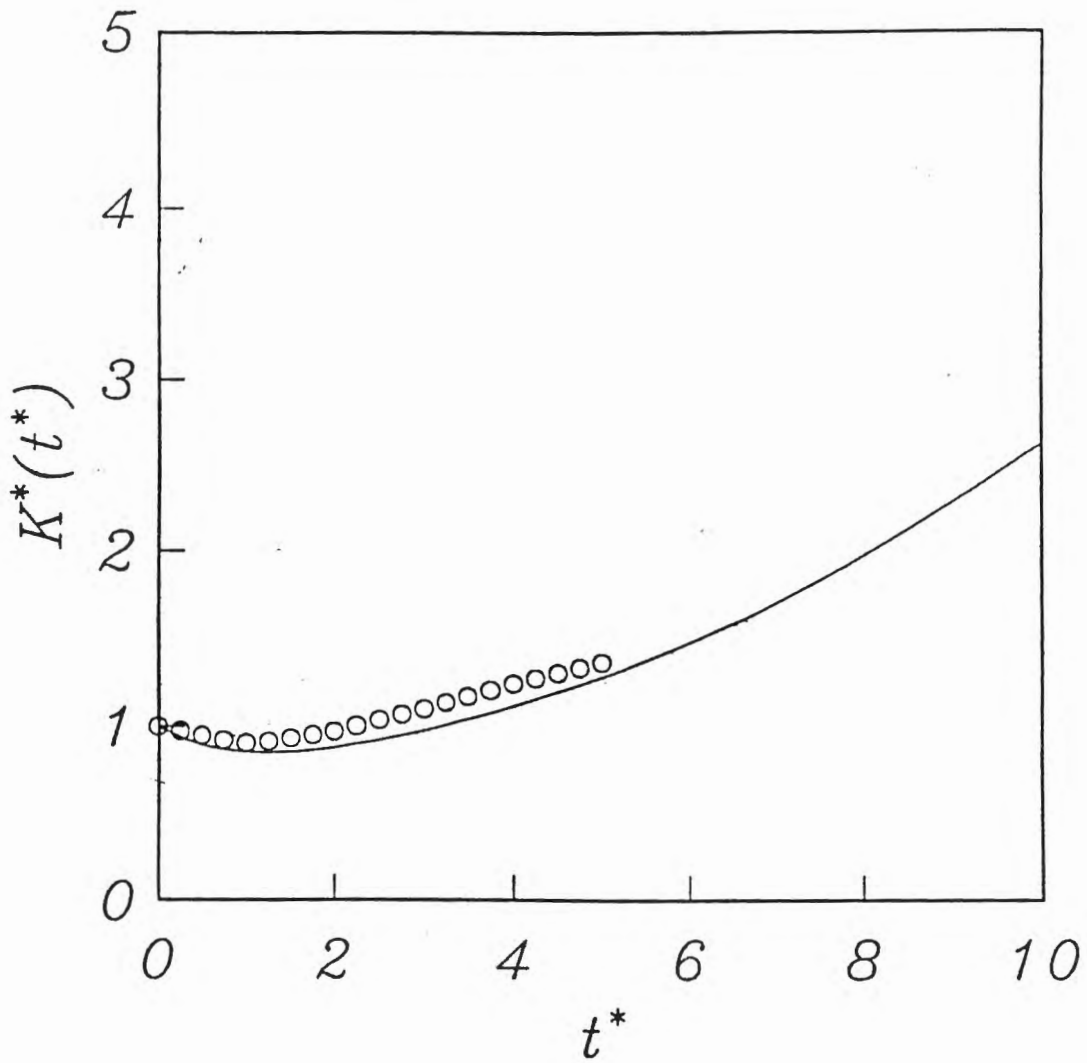
$$d(k/\nu \varepsilon) = 1.63 \nu dv/Y_1$$

$$Y_1 = [(v/v_0)^3 - 1 + C]^{1/2}$$

$$|(\alpha_k - 1.3930)/0.3930|^{0.6321}$$

$$\cdot |(\alpha_k + 2.3930)/3.3930|^{0.3679} = v_0/v_R$$

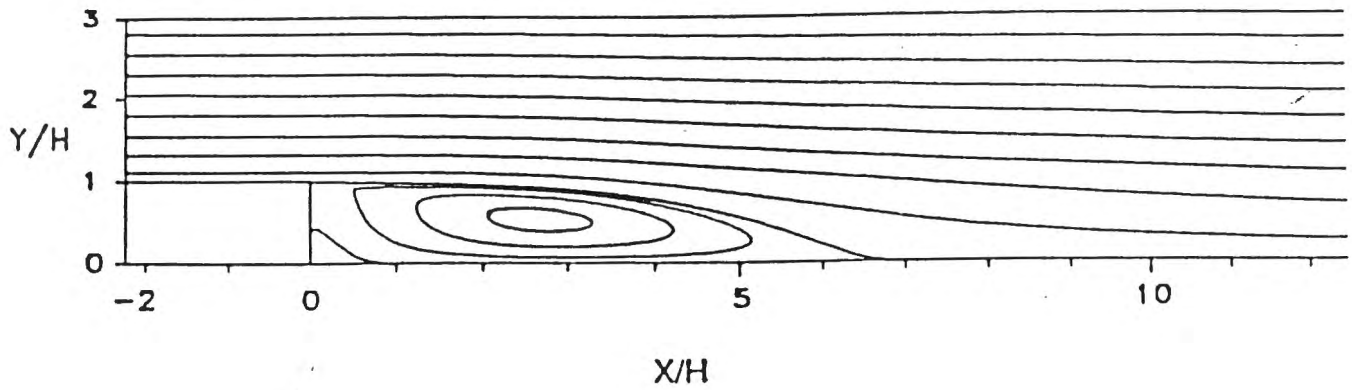
$$\alpha_\varepsilon = \alpha_k$$



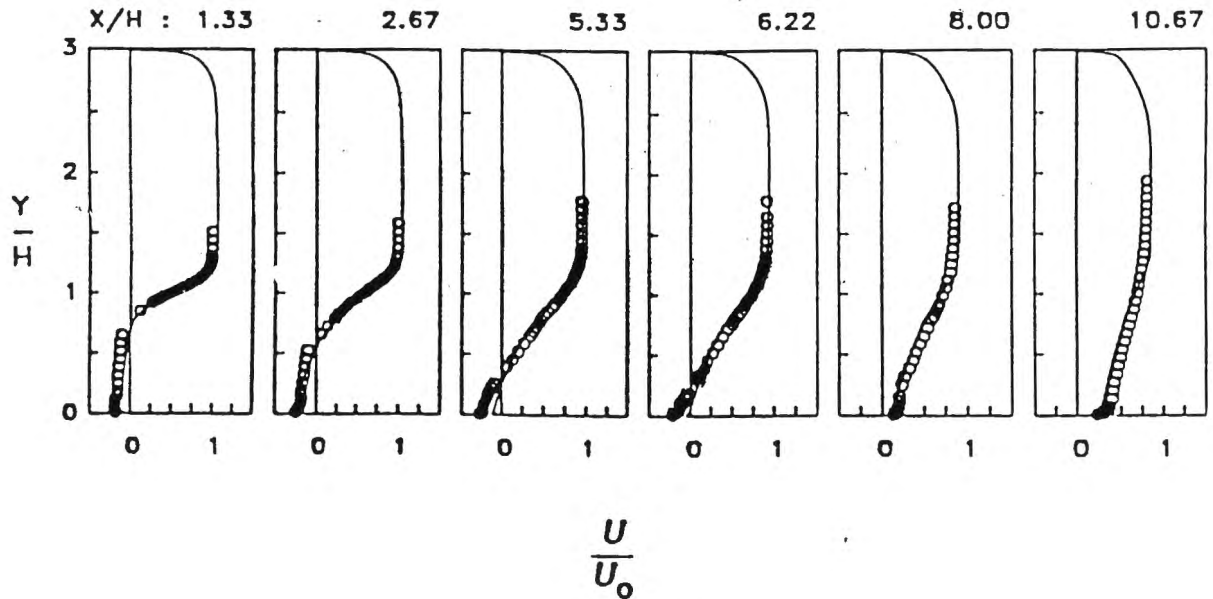
Time evolution of the turbulent kinetic energy in homogeneous shear flow.
 — Relaxation model; o Large-eddy simulation of Bardina *et al*¹⁴ for $\epsilon_0/SK_0 = 0.296$

Figure 2

BACKWARD-FACING STEP:



(a) Streamlines



(b) Dimensionless mean velocity profile

(— Computations with isotropic eddy viscosity;
o Experiments of Kim *et al*, 1980; Eaton & Johnston, 1981)

Computed mean flowfield for the new RNG $K-\epsilon$ model
[$E = 1:3$; $Re = 132,000$; 200×100 mesh]

Figure 4



FIGURE 10. Aluminum-powder pictures of streamlines over a step. Exposure time 0.5 (upper) and 5 seconds (lower).



(a) Reattachment at $X/H = 7.0$



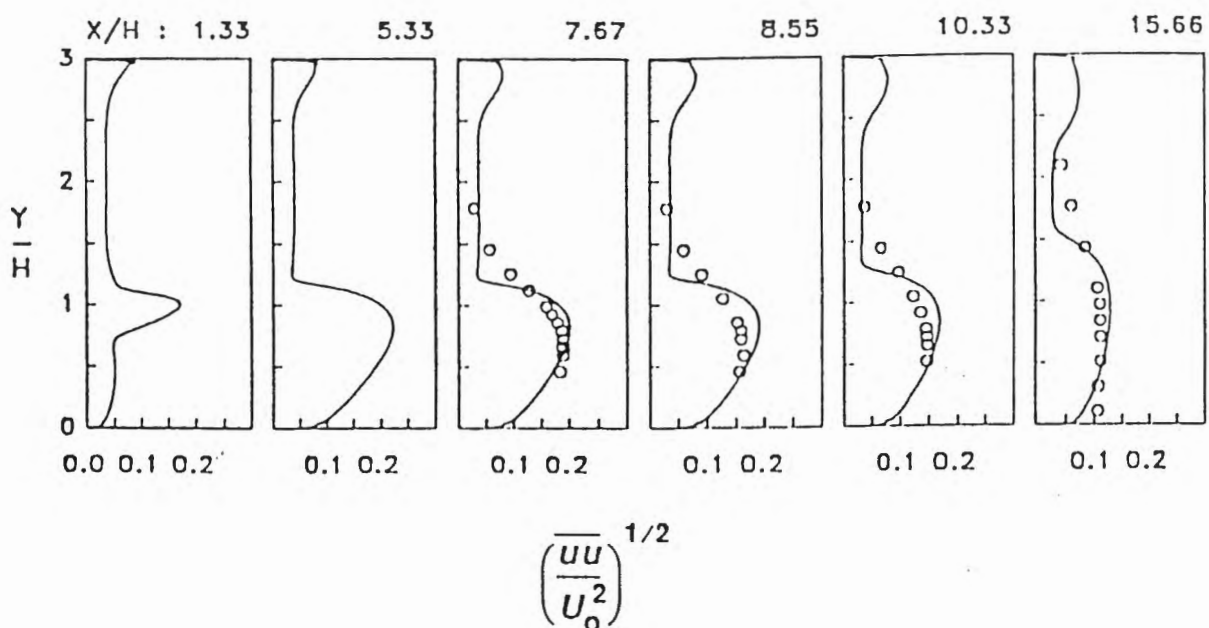
(b) Primary recirculation zone



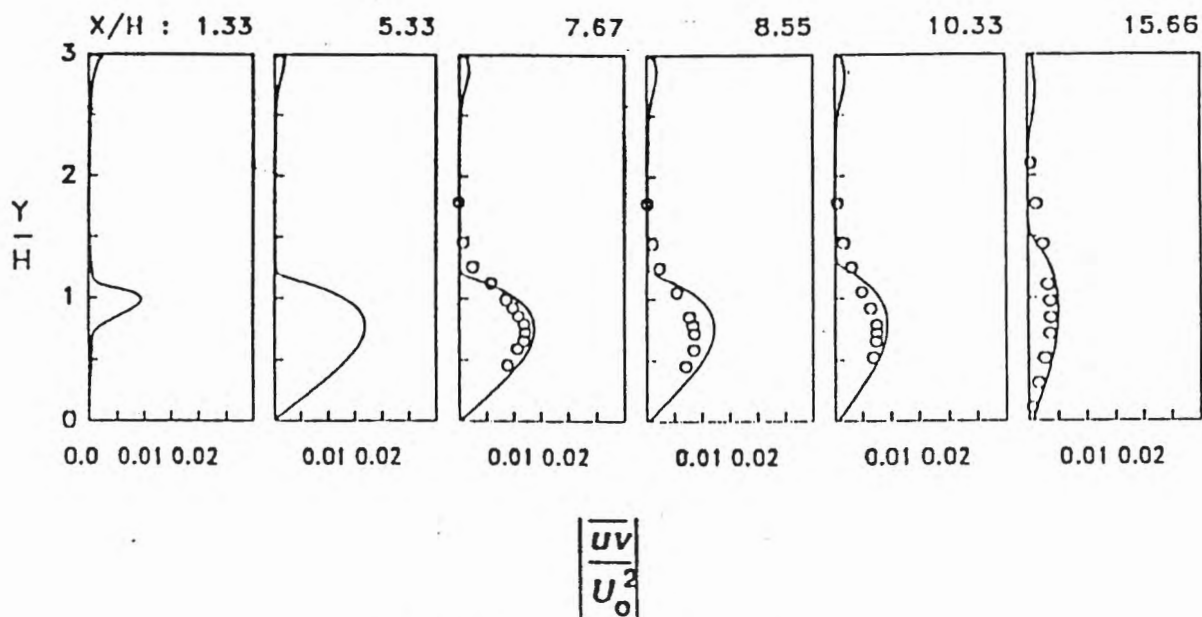
(a) Corner eddy

Streamlines for the flow over a backward facing step computed using the RNG $K-\epsilon$ model ($Re = 88000$, $E=2:3$)

BACKWARD-FACING STEP:



(a) Turbulence Intensity

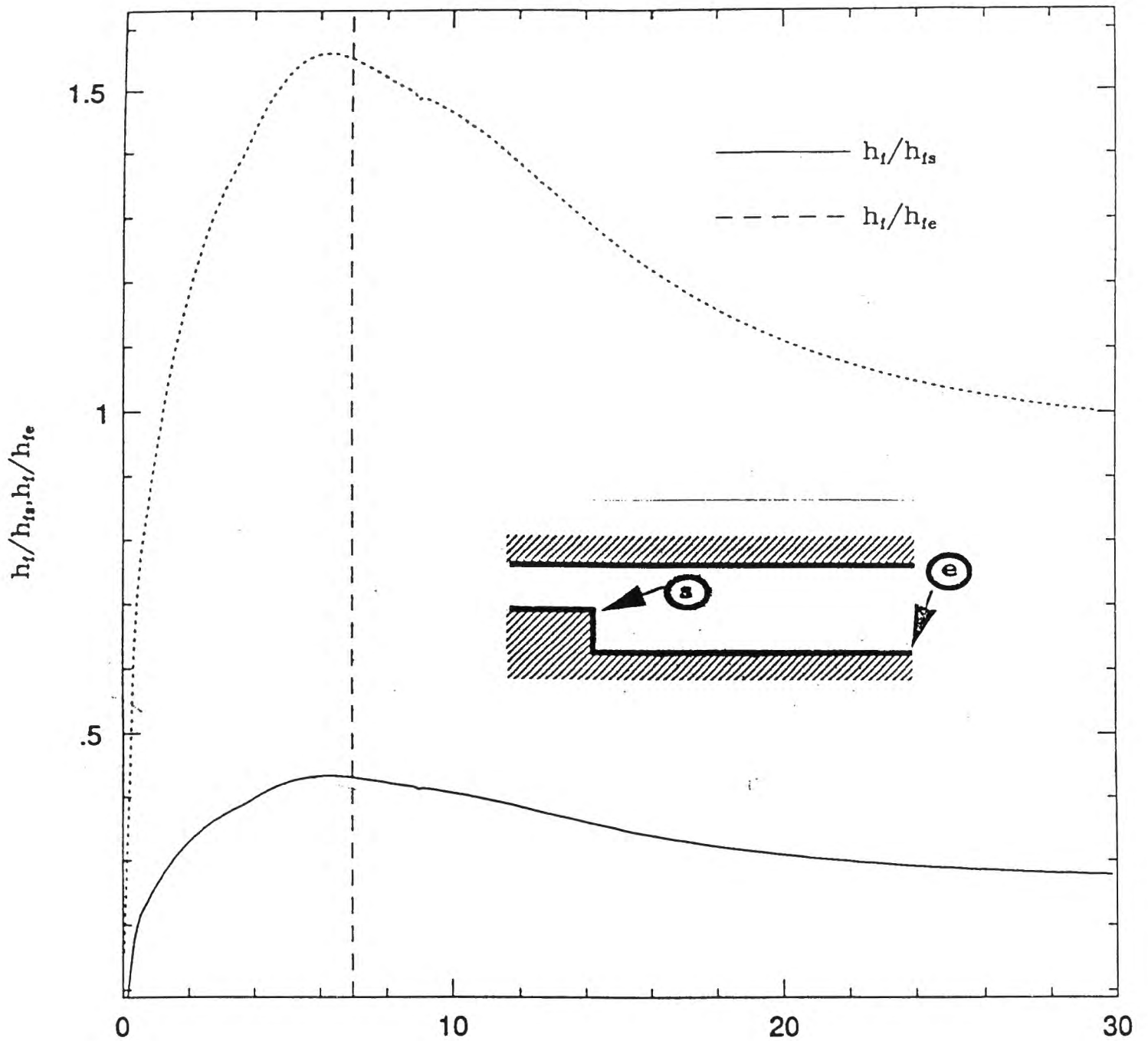


(b) Turbulence shear stress

Computed turbulence stresses for the new RNG $K-\epsilon$ model [$E=1:3$; $Re = 132,000$; 200×100 mesh; — computations with anisotropic eddy viscosity; o experiments of Kim *et al*, 1980; Eaton & Johnston, 1981]

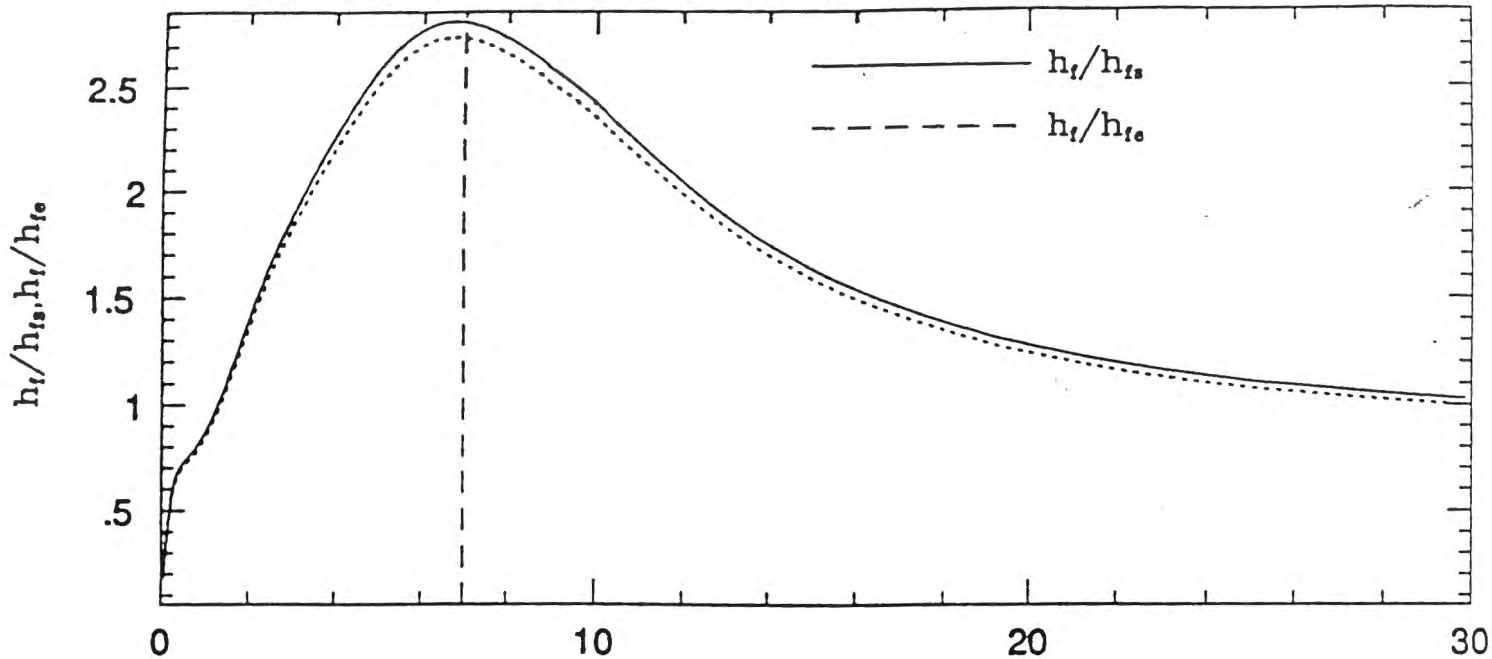
Figure 7

RNG K- ϵ model with RNG heat transfer for air, $\sigma_0 = 0.7$)

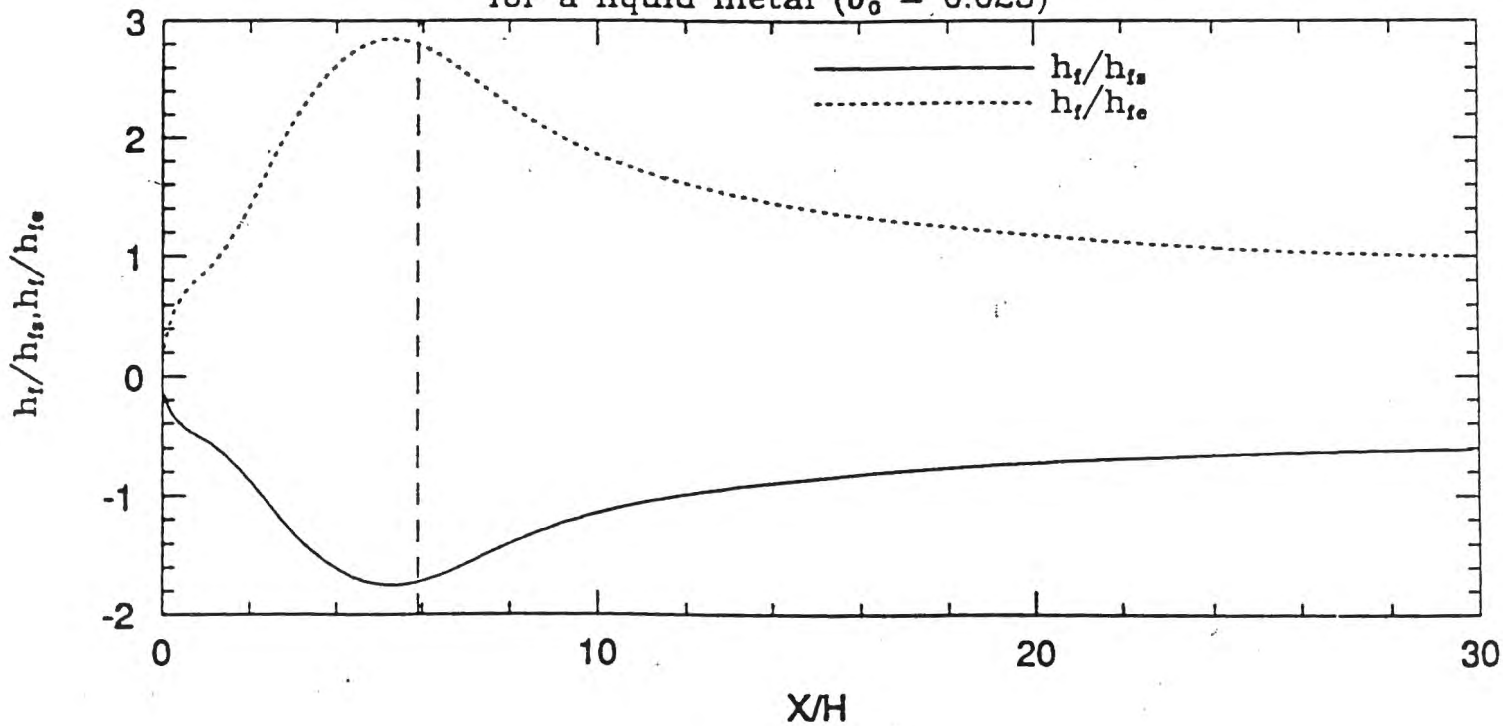


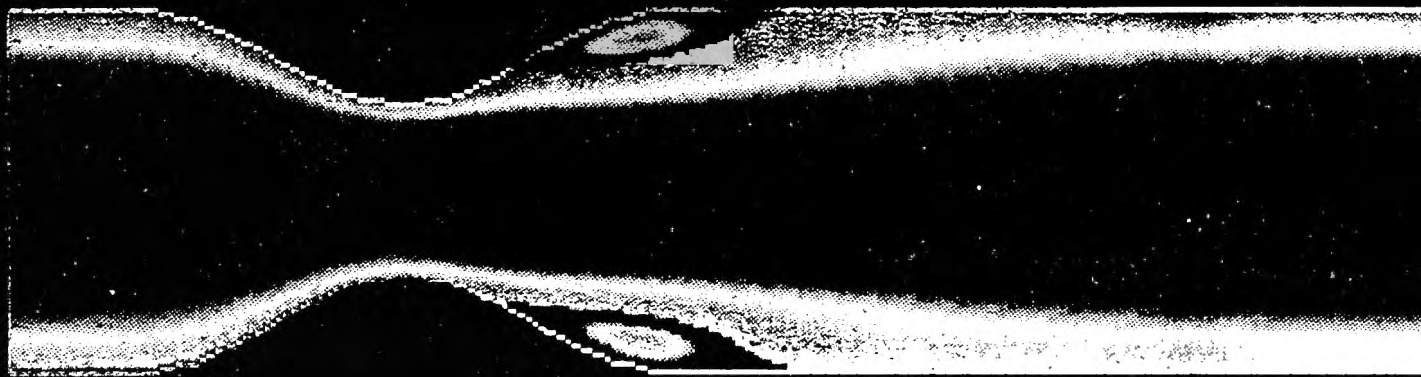
Heatflux ratios for the air flow over a backward facing step computed using the RNG K- ϵ model, $Re = 88,000$, $E = 2:3$, $\sigma = 0.7$. (h_{fs} = heat flux at the step corner, h_{fe} = heat flux at the exit)

RNG K- ϵ model with RNG heat transfer (liquid metal, $\sigma_0 = 0.025$)



Standard K- ϵ model with standard heat transfer for a liquid metal ($\sigma_0 = 0.025$)





Streamlines for the flow in a constricted pipe computed using the standard $K-\epsilon$ model ($Re = 10,000$, $D_{throat} / D_{in} = 0.5$)



**Streamlines for the flow in a constricted pipe at computed using the
RNG $k-\epsilon$ Model ($Re = 10,000$, $D_{throat} / D_{in} = 0.5$)**

2-56

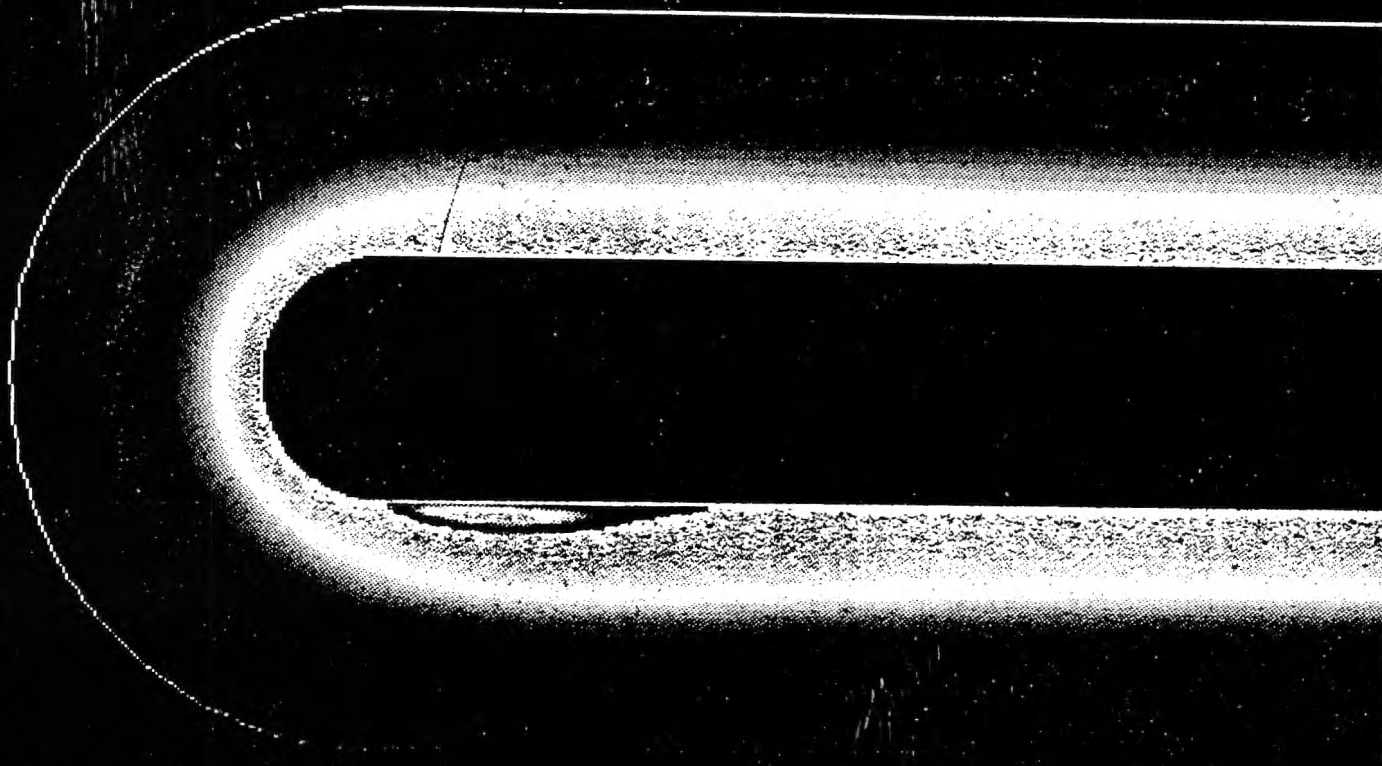


Turbulent Flow in a Turnaround Duct - Standard k- ϵ
Grid

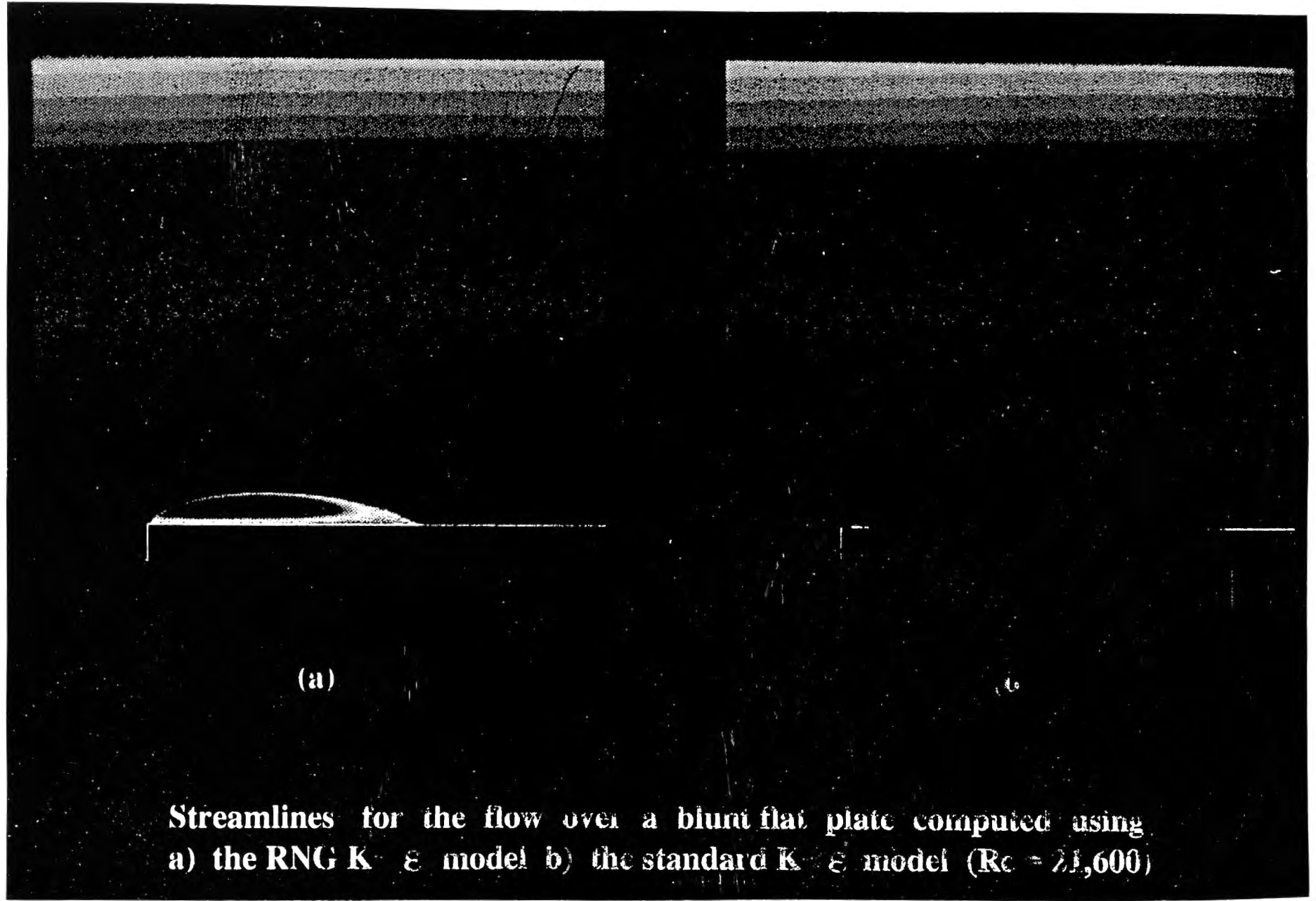
05/17/92
Fluent 4.11
Fluent Inc.

1.54E+00
1.49E+00
1.44E+00
1.39E+00
1.33E+00
1.28E+00
1.23E+00
1.18E+00
1.13E+00
1.08E+00
1.03E+00
9.71E-01
9.15E-01
8.59E-01
8.03E-01
7.47E-01
6.91E-01
6.35E-01
5.79E-01
5.23E-01
4.67E-01
4.11E-01
3.55E-01
2.99E-01
2.43E-01
1.87E-01
1.31E-01
7.55E-02
1.99E-02
9.71E-17

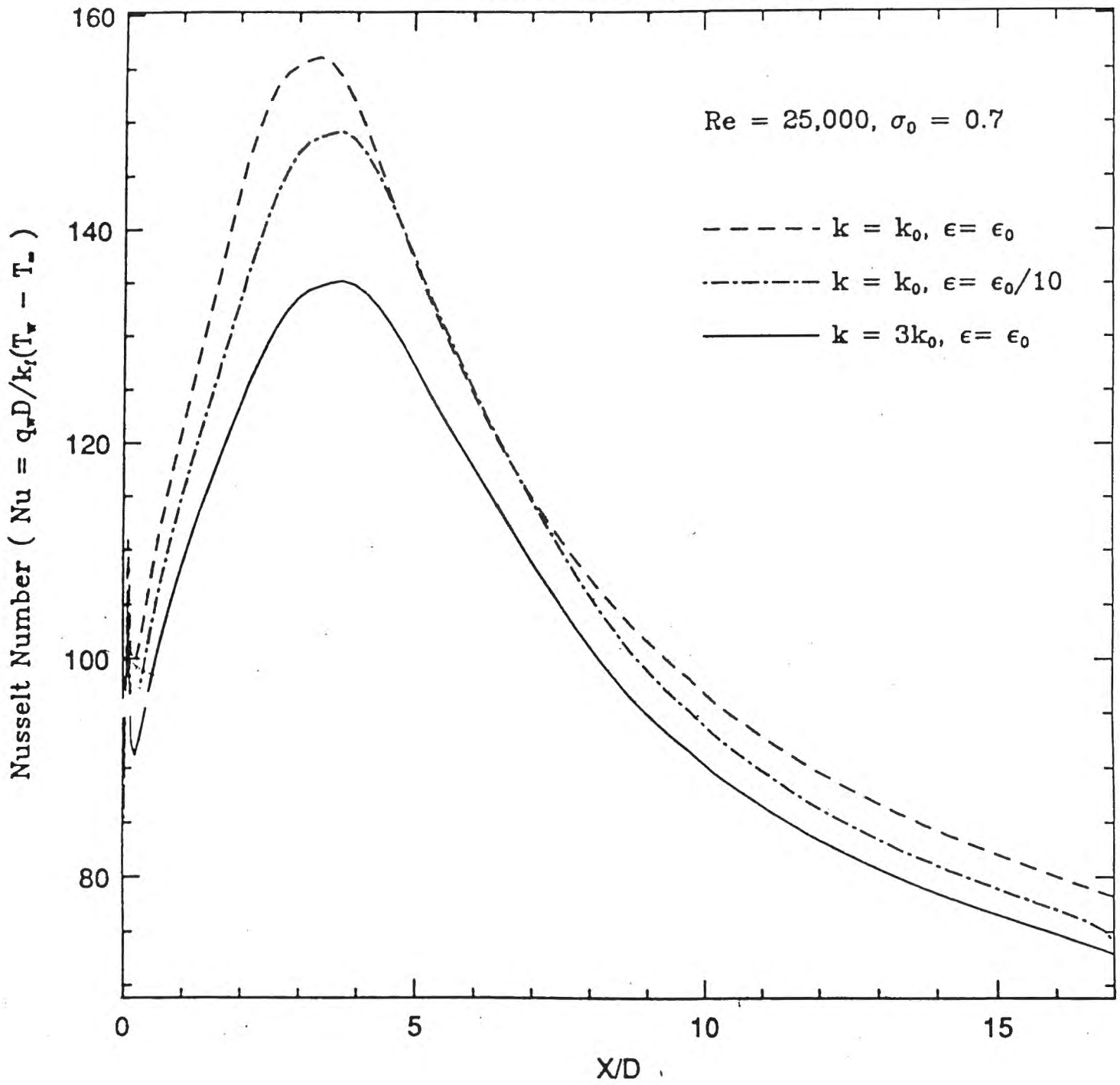
Streamlines for the flow in a turnaround duct computed using the standard K- ϵ model

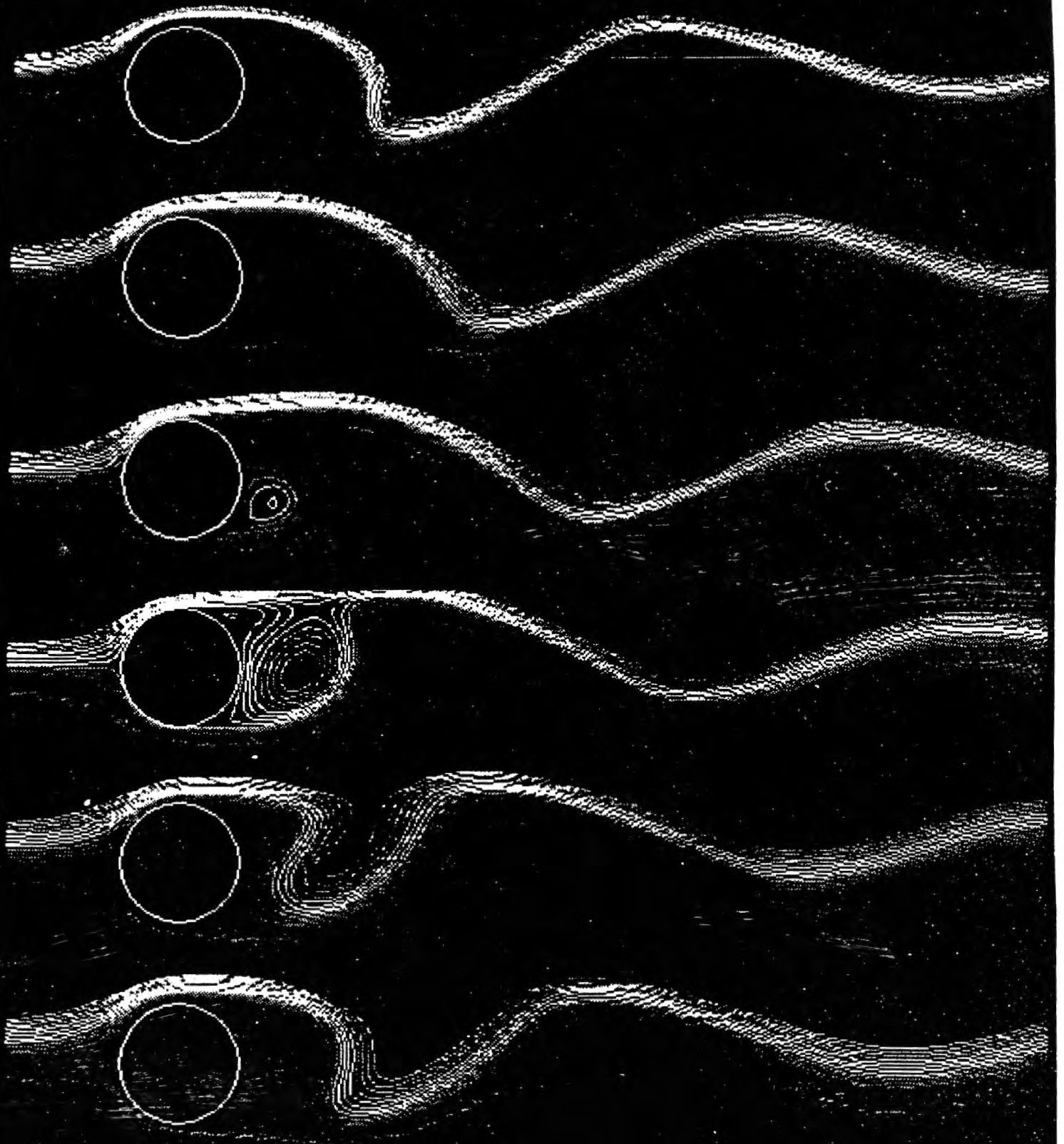


Streamlines for the flow in a turnaround duct computed using
RNG $k-\epsilon$ Model ($Re = 10^5$)

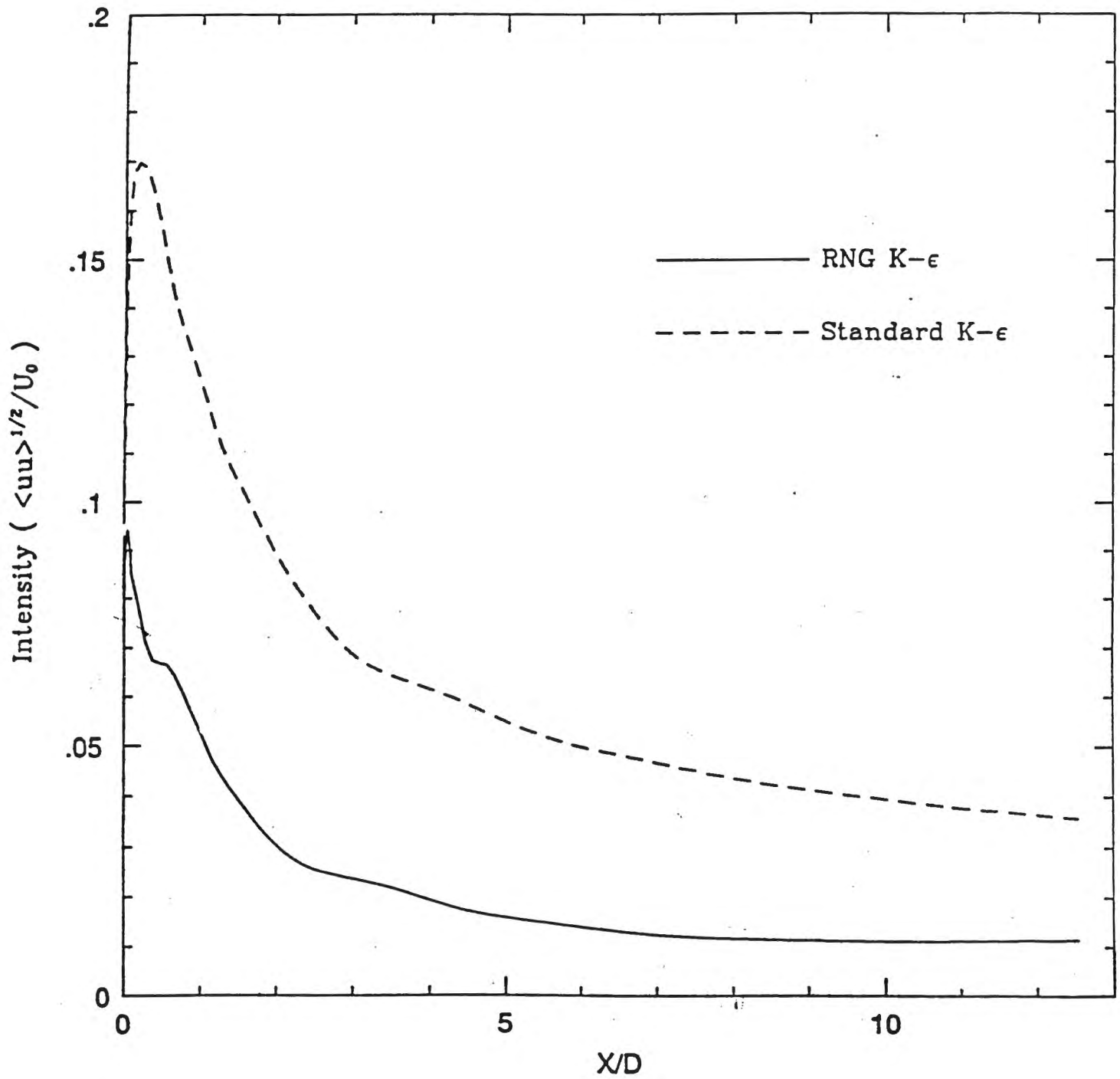


Sensitivity of Nusselt number to inlet turbulent conditions
for flow over a blunt flat plate





Streamlines in the wake of a cylinder at $Re=14,500$ computed using the RNG $K-\epsilon$ Model



Comparison between the RNG and standard K- ϵ models of the average turbulence intensity in the wake of the cylinder at $Re = 14,500$.



Pressure contours in the flow over a cylinder at $Re = 14,500$ computed using the RNG $K-\epsilon$ Model

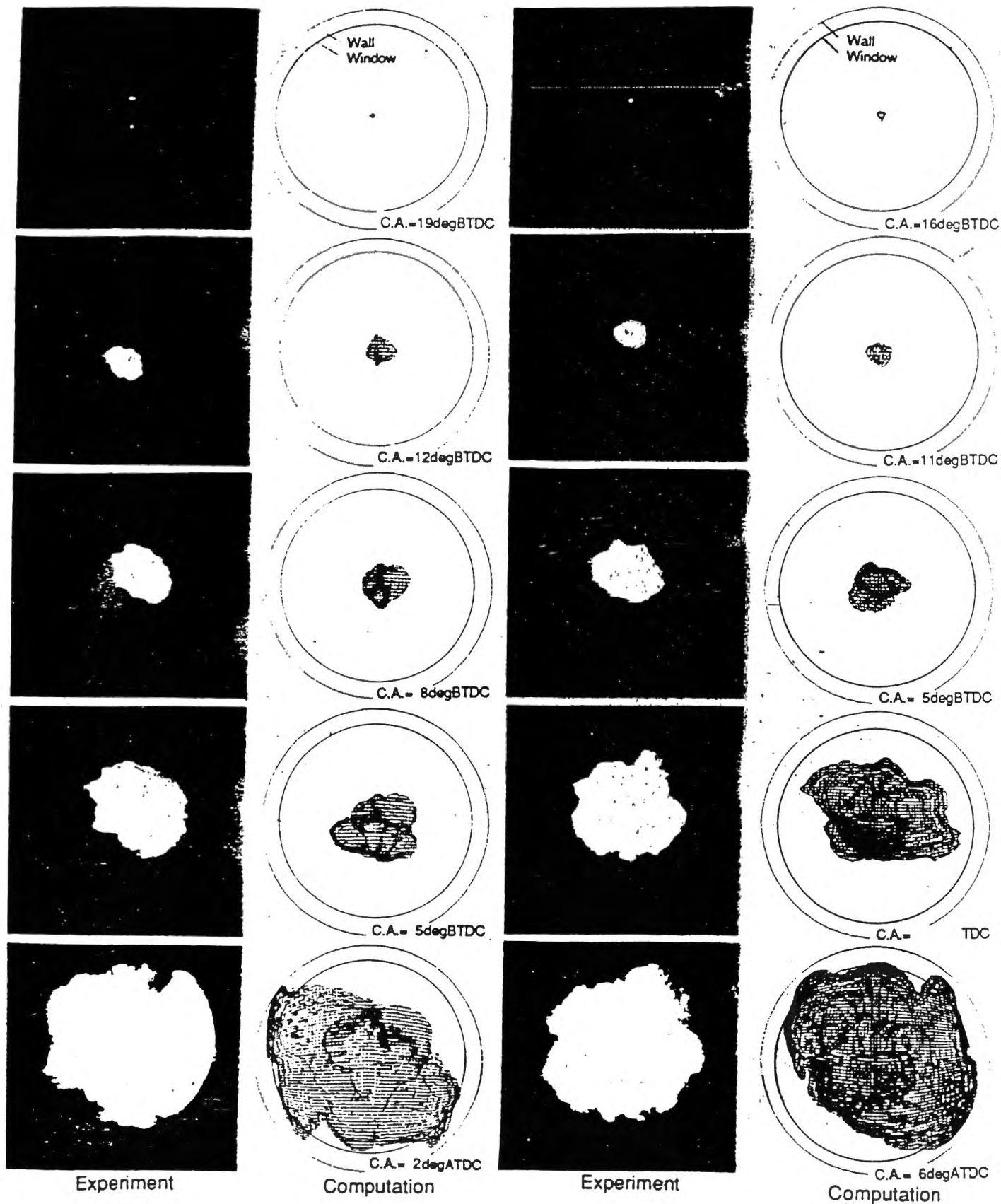


Fig. 11 The computed and experimental flame-propagation process in a 4-valve engine (CASE A-II) Engine speed = 1400rpm,

Fig. 12 The computed and experimental flame-propagation process in a 4-valve engine (CASE A-III) Engine speed = 2100rpm,

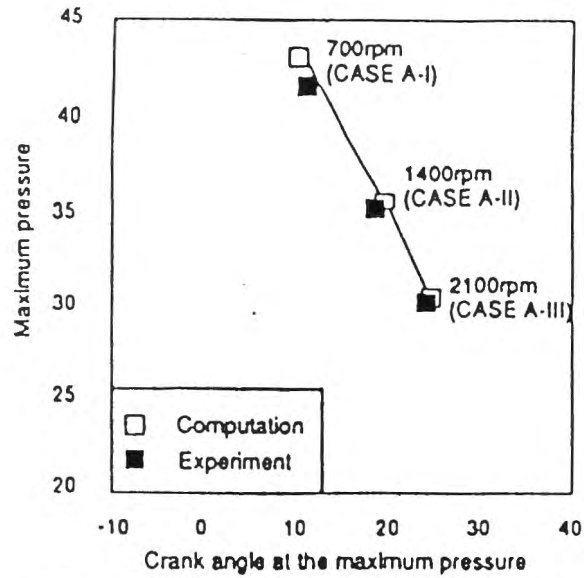


Fig.14 The comparison of the computed maximum pressure with the experimental data (Engine speed variation)

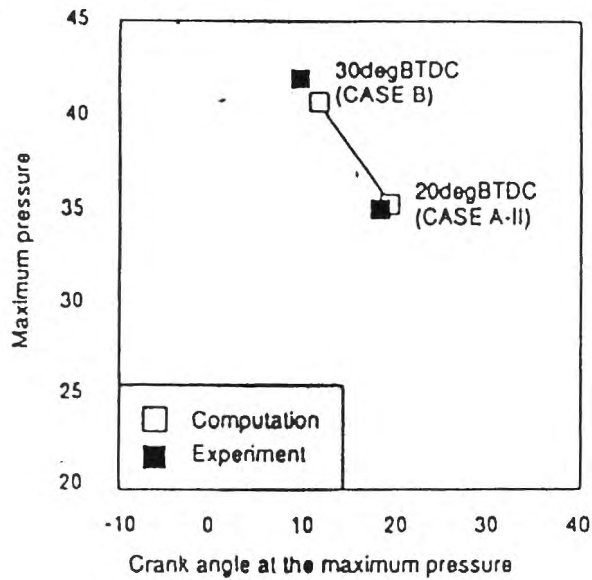


Fig.15 The comparison of the computed maximum pressure with the experimental data (Ignition timing variation)

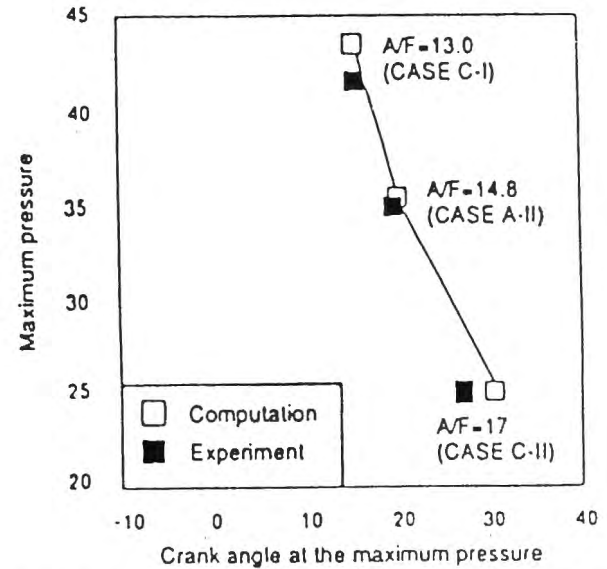


Fig.16 The comparison of the computed maximum pressure with the experimental data (A/F ratio variation)

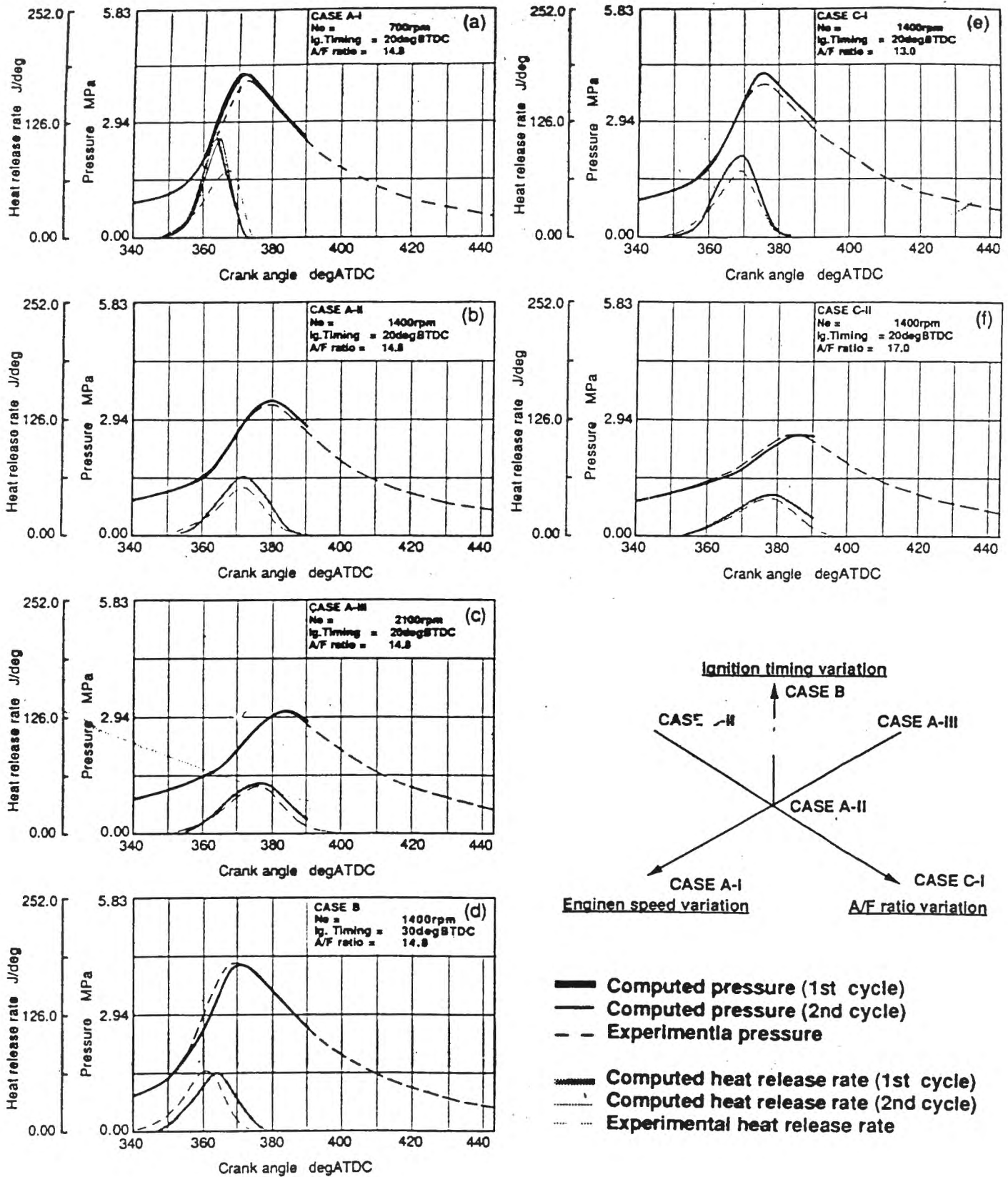


Fig. 13 The time histories of the computational- pressure and heat release rate and the corresponding experiments (a) CASE A-I, (b) CASE A-II, (c) CASE A-III, (d) CASE B, (e) CASE C-I, (f) CASE C-II

RNG Turbulence Modeling

1. Continuous spectrum of models
DNS \rightarrow LES \rightarrow RANS
- Determined by mode cut off
2. Basic physics models are key
 - Derivation
 - Test / Even simple models can have a lot of physics built in
 - \ Understand limits of validity of model
3. K- ϵ OK for general separated, non-equilibrium flows
OK up to swirl #s $O(1)$
Anisotropic models needed for larger swirl #s
Limits yet unknown but RSM may not be needed
4. Turbulence structure can be obtained by modeling even at K- ϵ level
5. DNS may be at misleadingly low Re
 - Models critical

3. Direct Control of Wall Shear-Stress in a Turbulent Boundary Layer

**Daniel Nosenchuck and Garry Brown
Princeton University**

SEMINAR NOTICE

DIRECT CONTROL OF WALL TURBULENCE USING
ELECTROMAGNETIC FORCES

Professor Daniel M. Nosenchuck

and

Professor Garry L. Brown

Princeton University

A new concept and technique has been developed to directly control turbulence production in boundary layers. Near-wall vertical motions are directly suppressed through the application of a Lorentz force. Current (\mathbf{j}) and magnetic (\mathbf{B}) fields parallel to the boundary and normal to each other produce a finite Lorentz force $\mathbf{j} \times \mathbf{B}$ normal to the boundary. Experiments have been performed on flat-plate turbulent boundary layers at $Re_\theta = 1700$. With the application of modest field densities (eg. $|\mathbf{B}| < 500$ gauss and $|\mathbf{j}| < 10$ mA/cm²), measured reductions in turbulent stresses within the control region are seen to exceed 90%. Laser-sheet flow visualization confirms the substantial reductions in turbulent motion at $y^+ \lesssim 15$. It is suggested that the principal reason for the observed effects is due to the direct control of the coherent motions responsible for turbulence production in the near-wall region.

Thursday, 24th September 1992

Conference Room A, Bldg. 102

Time: 10:30 AM

POC: Dr. Promode R. Bandyopadhyay (Code 8234; x2588)

Overview

- Turbulence is characterized by:
 - periodic eruptions of unstable, low-momentum 'near-wall' fluid
 - subsequent inrush of high-speed 'outer-flow' fluid
 - resultant large skin-friction drag
- Lorentz force easily generated:
 - surface electrodes produce electric field with current density j
 - magnetic field B is generated parallel to surface and normal to electric field
 - resultant normal force is $j \times B$
- Direct application of wall-normal force could prohibit lift-up and bursting of near-wall fluid

MHD

Lo σ
Saltwater
Electrolytes
Plasma

Hi σ
Liquid
Metals

Internal
Flows

External
Flows

Internal
Flow

External
Flows

Propulsion
Power gen.

TFMs

Pipe
flow control

lfc / tfc
Heat xfer
Noise

"Classic
MHD"
eg Direct
turb duct-
flow
suppression
studies

Stream-
lining;
wake
control

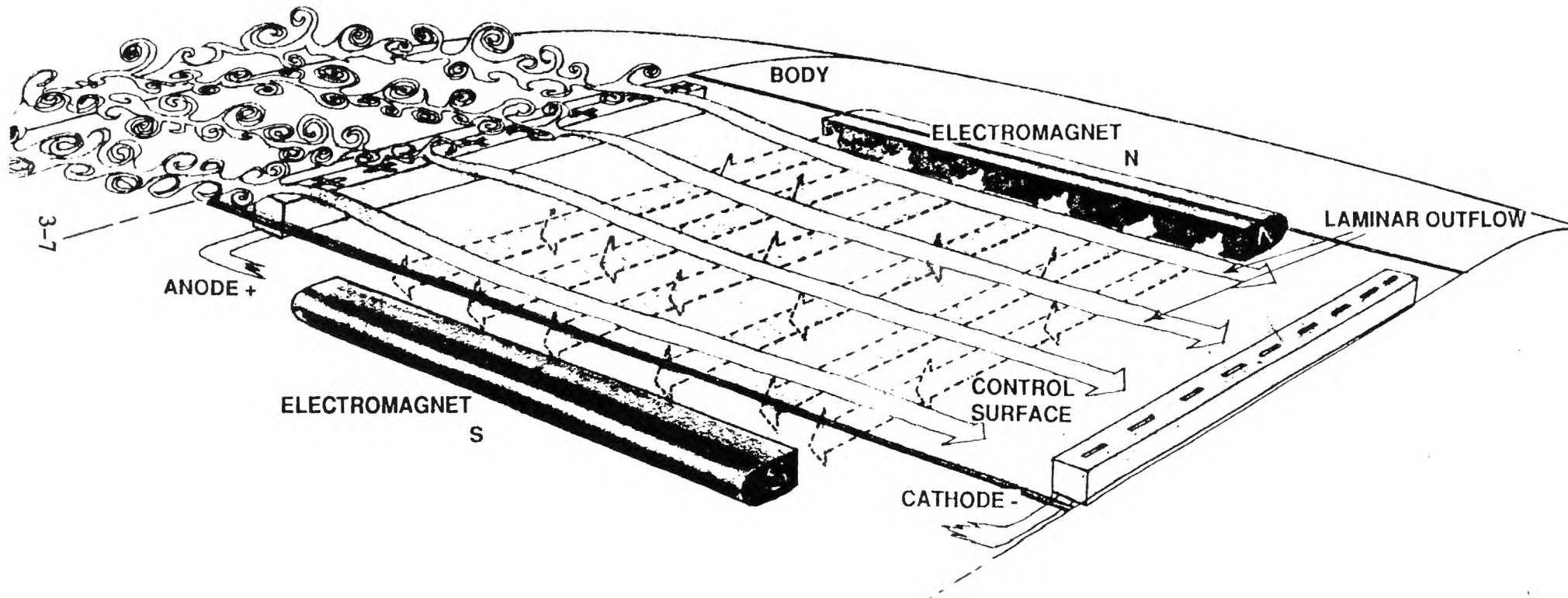
$$\left| \frac{\vec{u} \times \vec{B}}{E} \right| \ll 1$$

local, boundary
spatial u fields

$$\left| \frac{\vec{u} \times \vec{B}}{E} \right| \gg 1$$

external
spatial macro fields

TFM DETAILED CONCEPT



Elementary Concepts

MHD Similarity

- Assume 1-D flow; applied magnetic field B_0 , characteristic length L , velocity U , conductivity σ , density ρ , viscosity μ , permeability C_μ
- Per unit volume:

$$F_v(\text{viscous force}) \sim \mu \frac{U}{L^2}$$

$$F_i(\text{inertia force}) \sim \rho \frac{U^2}{L}$$

$$F_{em}(\text{electromagnetic force}) \sim \sigma B_0^2 U$$

- Magnetic Reynolds Number (Re_m)

$$Re_m = \left(\frac{\text{induced magnetic field}}{\text{applied magnetic field}} \right) = \frac{C_\mu \sigma B_0 U L}{B_0} = C_\mu \sigma U L$$

- Hartmann number (Ha)

$$Ha = \sqrt{\frac{F_{em}}{F_\sigma}} \equiv B_0 L \sqrt{\frac{\sigma}{\mu}}$$

- Interaction Parameter (I) (or Stuart Number)

$$I = \frac{F_{em}}{F_i} \equiv \frac{\sigma B_0^2 L}{\rho U}$$

Theoretical Considerations

- MOMENTUM

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mathbf{L} + \mu \nabla^2 \mathbf{u}$$

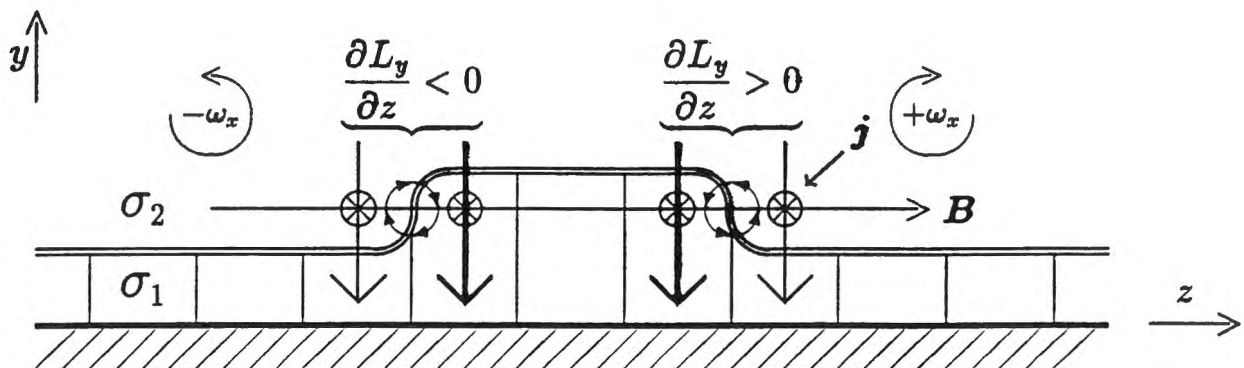
where $\mathbf{L} = \mathbf{j} \times \mathbf{B}$ (Lorentz force)

- VORTICITY

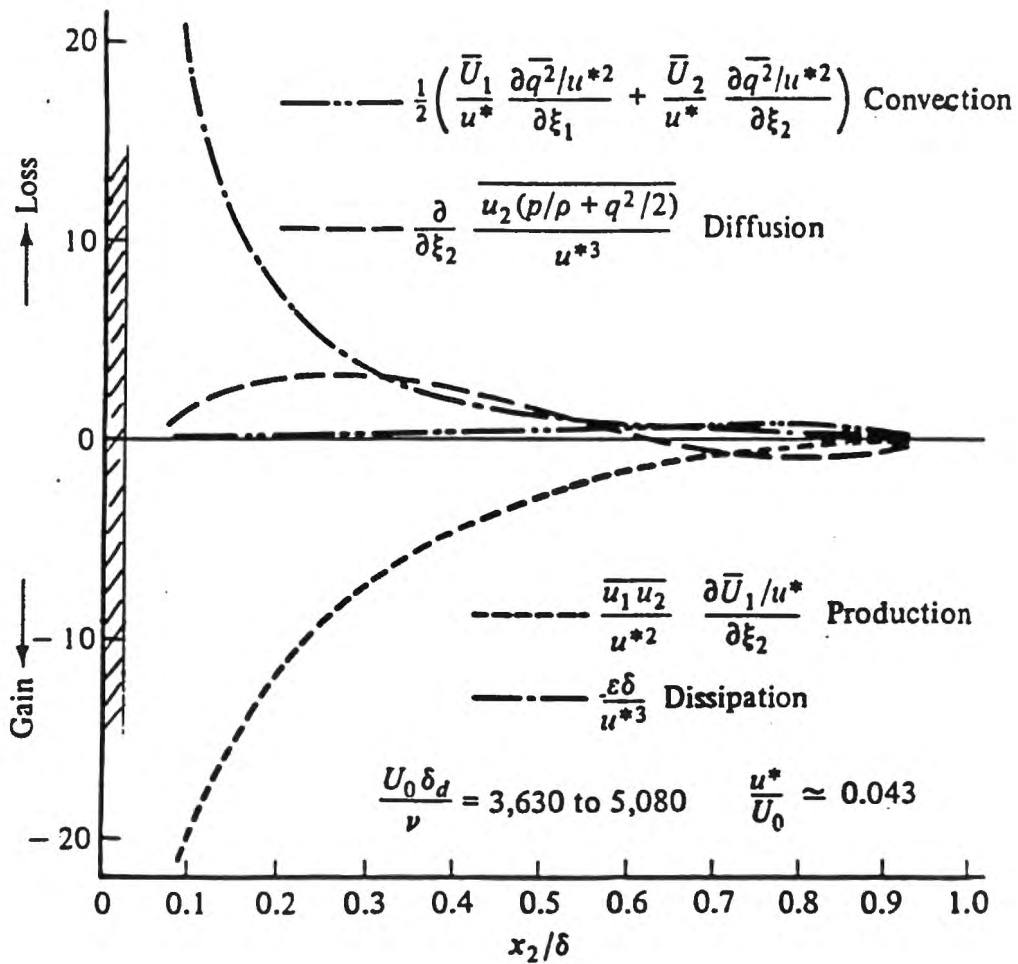
$$\rho \frac{D\omega}{Dt} = \rho \omega \cdot \nabla \mathbf{u} + \nabla \times \mathbf{L} + \mu \nabla^2 \omega$$

if $\mathbf{L} = L_y \mathbf{e}_j$:

$$\rho \frac{D\omega_x}{Dt} = \rho \omega_x \cdot \nabla \mathbf{u} - \frac{\partial L_y}{\partial z} + \mu \nabla^2 \omega_x$$



Turbulent Boundary Layer Energy Balance



//////////////////// : MTC Control Layer

Theoretical Considerations - Continued

- ENERGY

Near the wall

$$-u'v' \frac{\partial \bar{u}}{\partial y} \simeq \frac{\overline{L'_y v'}}{\rho} + \epsilon$$

Production \simeq Lorentz Work + Dissipation

this suggests the nondimensional parameter

$$\frac{\Delta L \nu}{\rho u_\tau^3}$$

for scaling Magnetic Turbulence Control

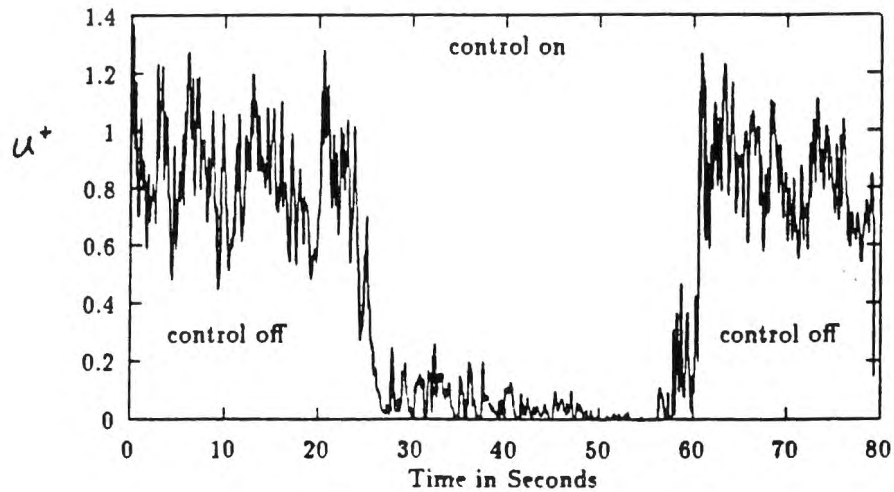
Some Engineering Considerations

- Fluid must be electrically conducting:
 - sea-water is an ideal electrolyte
 - small amounts of electrolytes injected near wall in fresh-water experiments
 - gaseous flows may be seeded with ions if plasma is not naturally present
- MTC power infinitesimal since
 - little mechanical work is done: $\overline{j \times B \cdot u} \sim 0$
 - Joule heating (σe^2) can be made negligibly small
- j and B fields may be DC or AC
- Distributed electrodes and magnet poles could generate fields that conform to non-planar surfaces

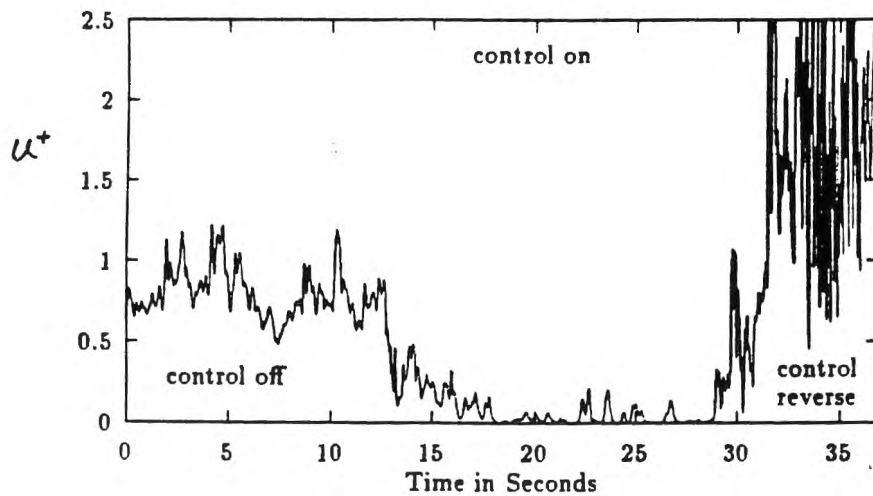
Experimental Investigation of MTC

- Turbulent boundary layer and turbulent-spot flows were studied on a flat plate in water
- Control region 8 cm wide and 16 cm long ($\sim 500 \times 1,000$ wall units) on \mathcal{C} of plate 200 cm from L.E.
- Control zone consisted of a lucite plate with
 - permanent magnets \Rightarrow transverse field ($B_y \sim 500$ gauss)
 - stainless-steel surface-mounted electrodes \Rightarrow longitudinal field ($0.003 < j_x < 20$ mA/cm²)
- $800 < Re_\theta < 1700$ upstream of control zone
- Dilute HCl, NaCl, and NaOH/fluorescein electrolyte injected normal to wall upstream of control zone
- Diagnostics included hot-film probes, gauss-meters, electric field sensors, laser-sheet flow visualization

Key Results



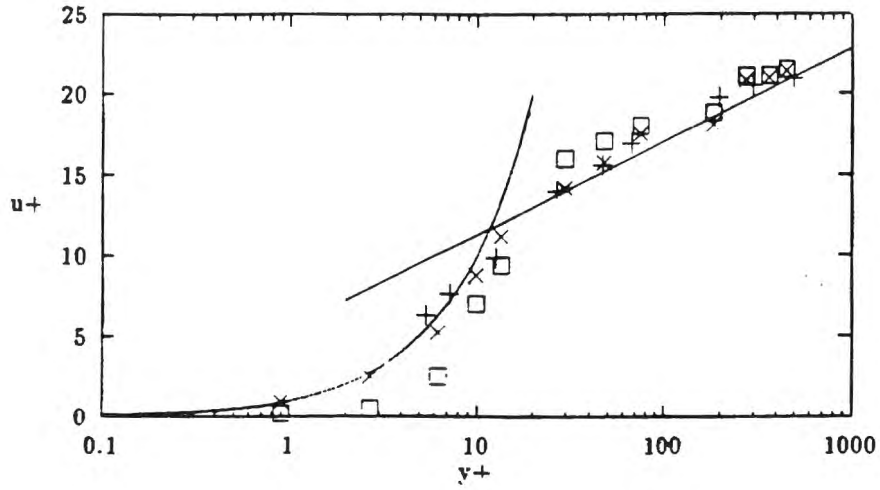
a: Control Sequence: Off-On-Off



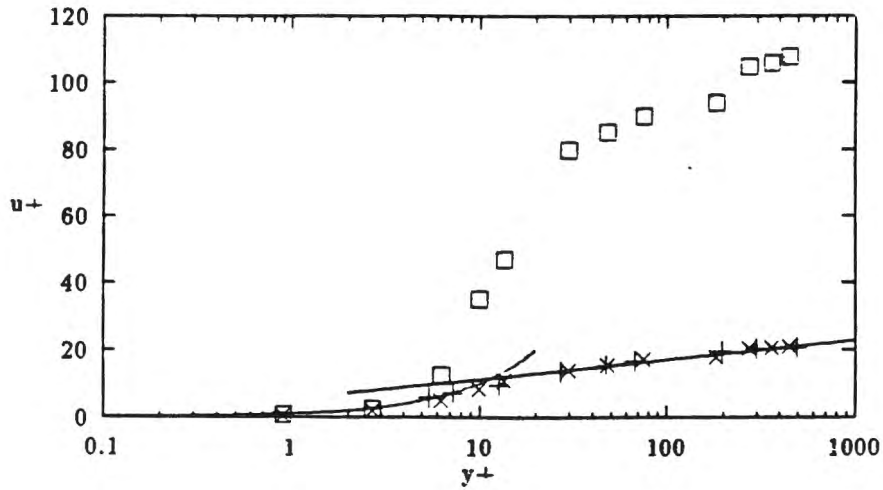
b: Control Sequence: Off-On-Reverse

MTC on Centerline at $y^+ \sim 1$
Velocity vs Time

- ×: No Electrolyte
- + : Electrolyte On; No Control
- : Control On: $j \times B < 0$

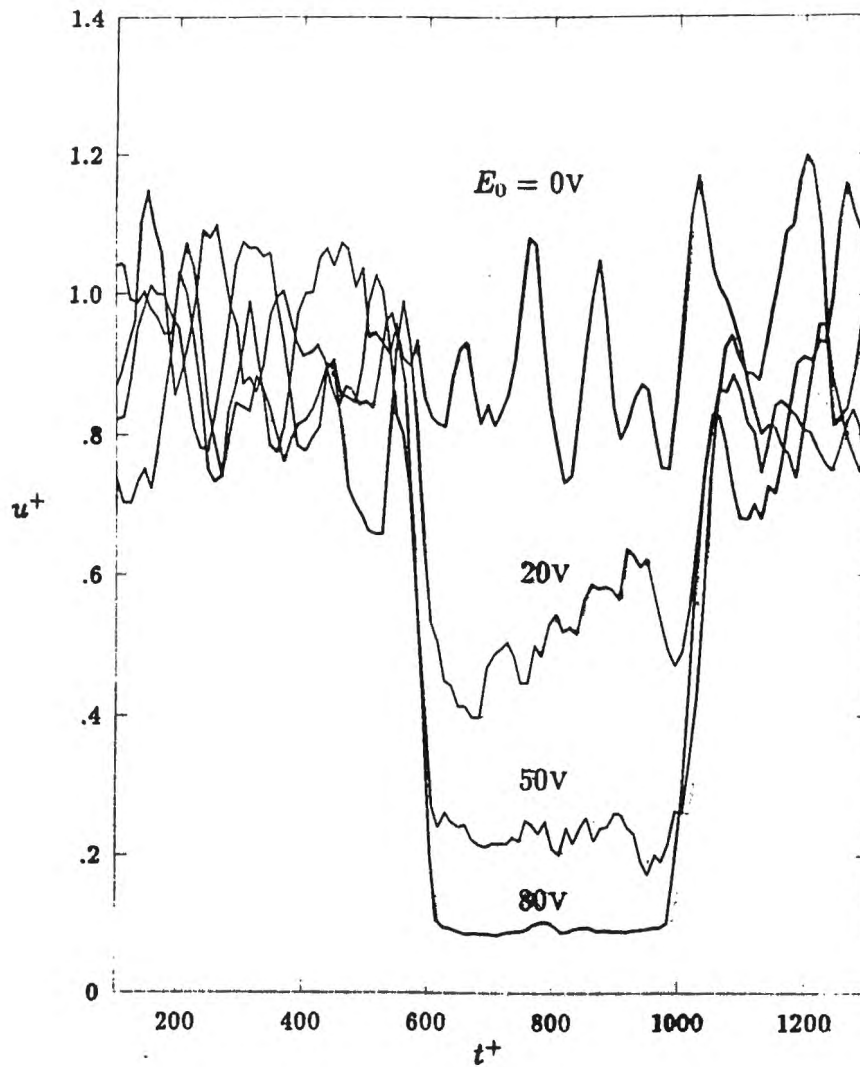


a: u_{τ} Computed from Baseline Profile



b: u_{τ} Computed for Each Case Separately

Effect of MTC on Mean Turbulent Boundary Layer Velocity Profile



Effect of Magnitude of Lorentz Force on Magnetic Turbulence Control

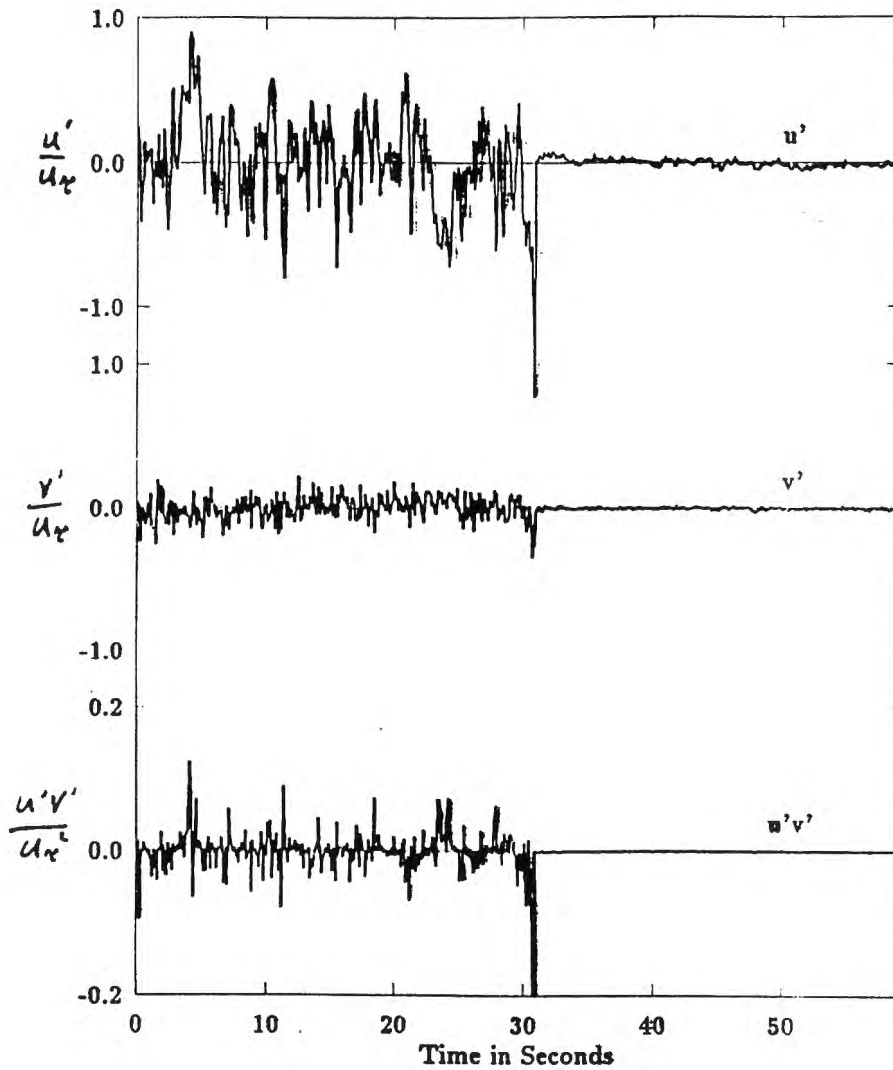
Velocity vs Time

$$y^+ \simeq \frac{1}{2} \quad Re_\theta \simeq 1700$$

Magnetic Turbulence Control

OFF

ON



Turbulent Motions and Stresses

Velocity vs Time

$$y^+ \sim 3 \quad Re_\theta \simeq 1100$$

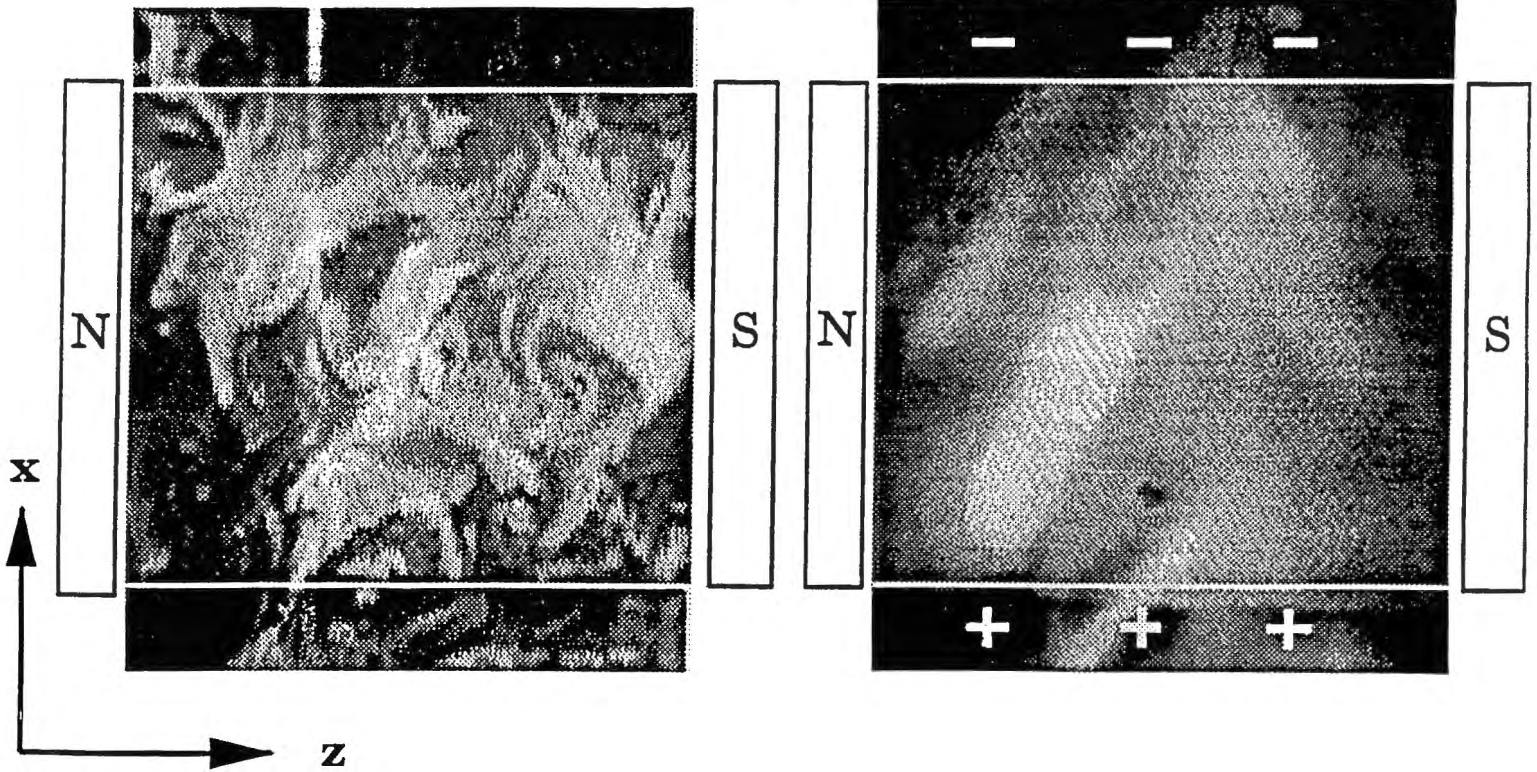
Direct Magnetic Control of a Turbulent Boundary Layer

$L_y = 0$

Planform View

$L_y < 0$

$y^+ < 5$



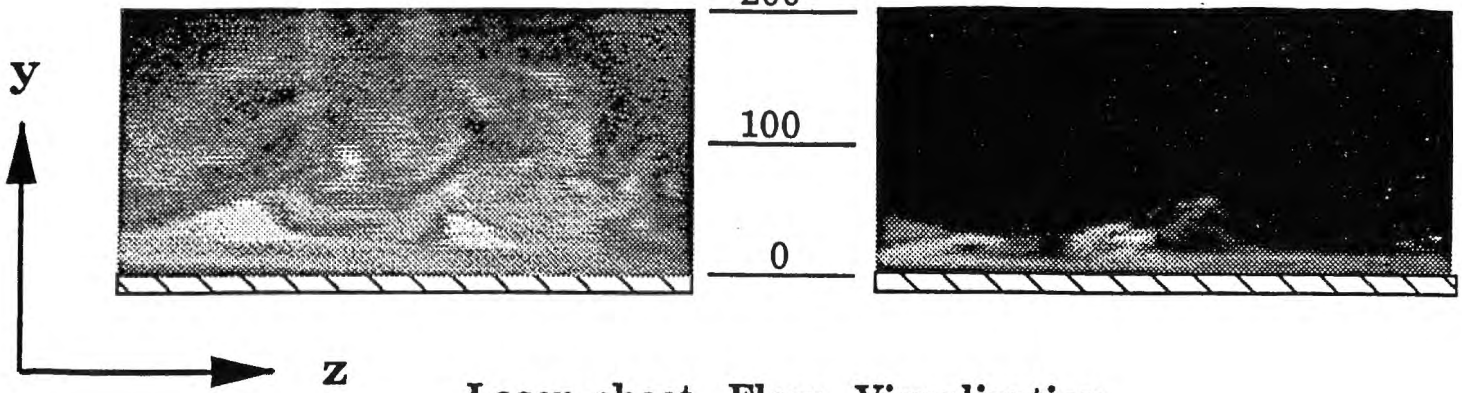
Elevation View

y^+

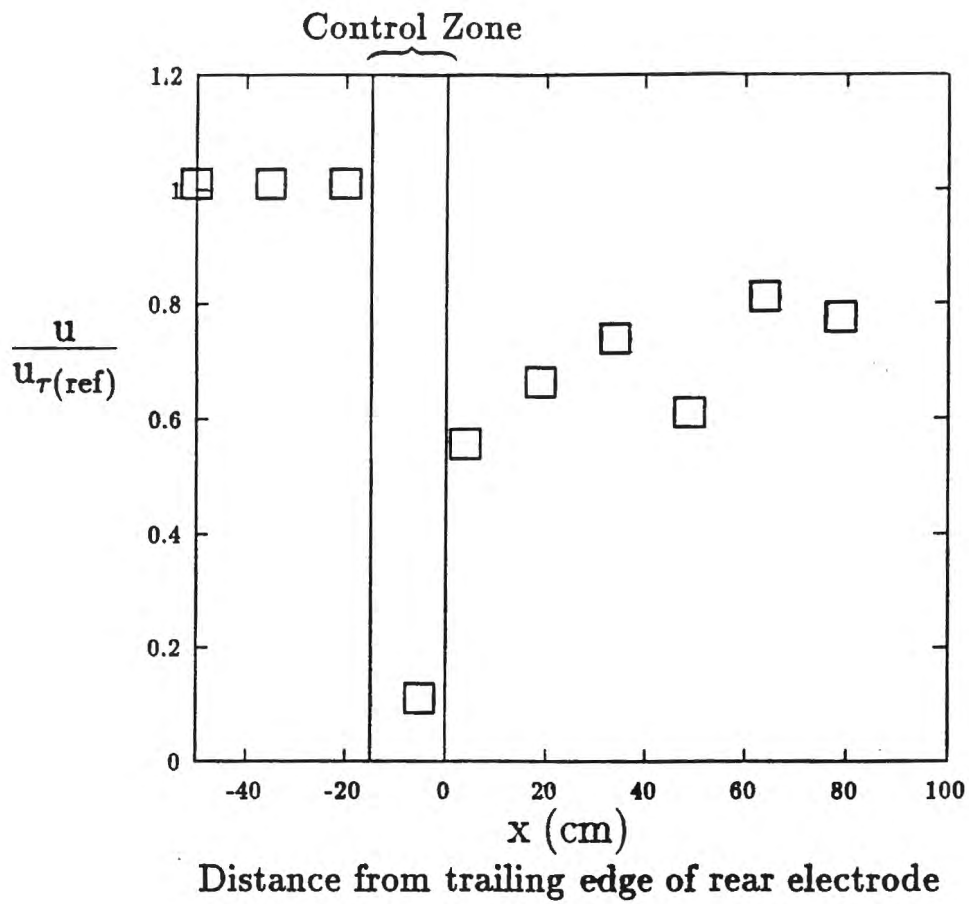
200

100

0



Laser-sheet Flow Visualization



MTC Relaxation

**Near-wall Longitudinal Velocity (Wall-Shear) Distribution
On Control Zone Centerline**

(Preliminary Results)

Other Applications

- Separation control
 - decrease or increase form drag
 - provide directional control through net lateral forces and moments
- Acoustic field attenuation/enhancement/tailoring
- Modification of unsteady surface pressure fields
- Turbulent fluid mixing
- Surface heat-transfer control:
 - $j \times B < 0 \Rightarrow$ decreased wall heating
 - $j \times B > 0 \Rightarrow$ enhanced wall heating

Summary of MTC

- A new concept and technique using electro-magnetic fields has been developed to suppress wall-turbulence
- Non-intrusive magnets and surface electrodes:
 - impart normal force $j \times B$ near wall in turbulent boundary layers
 - turbulence generation directly suppressed
- Proof-of-concept experiments have been performed in a water channel on a flat plate model
 - $> 90\%$ reduction in turbulent skin friction (drag)
 - near wall velocity fluctuations attenuated $> 5\times$
 - flow visualization indicates nearly 'laminar' flow
 - minimal power/current required

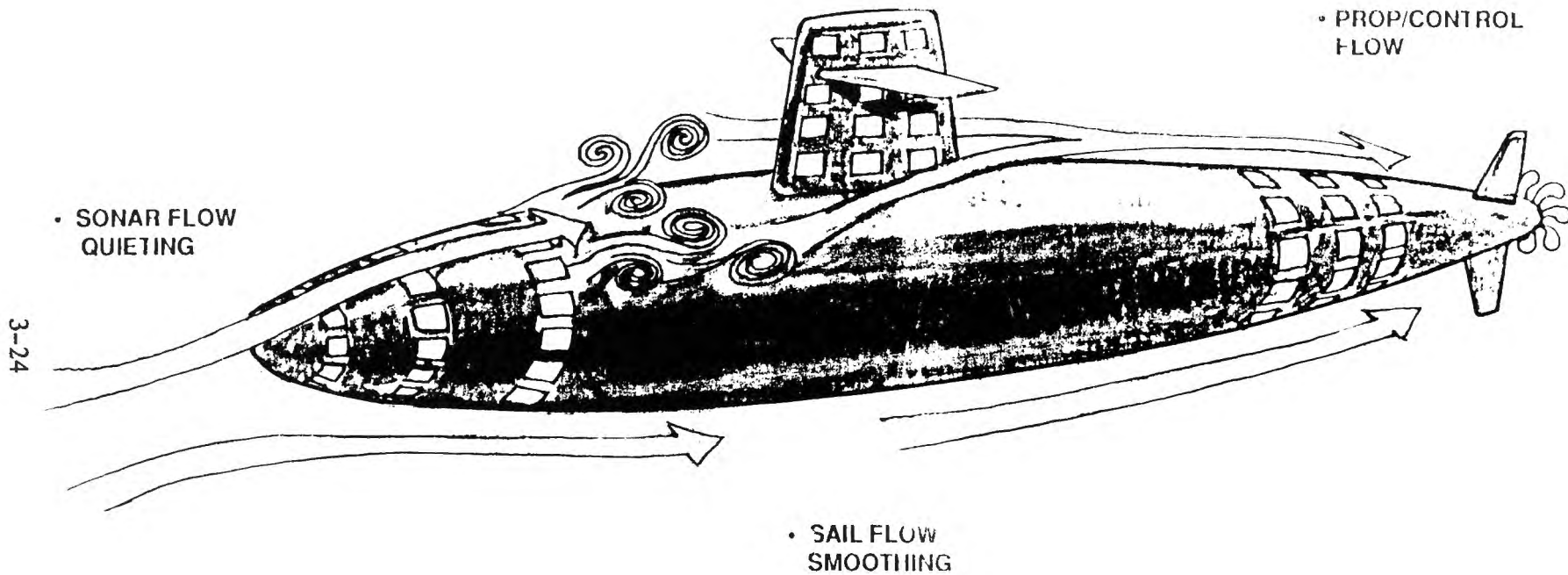
Questions

- High Reynolds number behavior
- Dependence on ion concentration and uniformity
- Underlying dimensionless parameters

$$\text{e.g. } \frac{\Delta L \nu}{\rho u_T^3}$$

- Relaxation, tiling, and three-dimensionality
- Frequency response; field attenuation
- Numerical simulation

TFM APPLICATION CONCEPT - SEA



4. Bluff-Body and Other Shear Flows

**Anatol Roshko
California Institute of Technology**

NUWC Division Newport, R. I.

SEMINAR NOTICE

BLUFF-BODY AND OTHER SHEAR FLOWS

Anatol Roshko

Theodore von Kármán Professor of Aeronautics

California Institute of Technology

The old problems of the far wake, near wake and forces on bluff bodies will be discussed, mainly the so-called two-dimensional flows behind circular cylinders and flat plates. Progress and problems in understanding the dynamics of the flow will be discussed. Topics include: effects of Reynolds number; effects of three dimensionality in nominally 'two dimensional flows'; roles of vortex dynamics and Reynolds stress; insights from experimental-computational interactions and from other shear flows.

Monday, 28th September 1992

Conference Room B, Bldg. 102

Time: 10:30 AM

POC: Dr. Promode R. Bandyopadhyay (Code 8234; x2588)

4-3/4-4

Reverse Blank

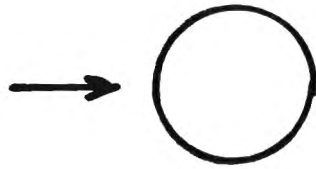
BLUFF-BODY NEAR WAKES

"SIMPLE" GEOMETRIES

2D

Axisymmetric

Circular
Cylinder



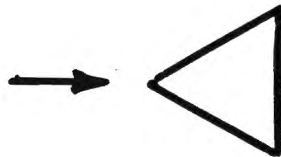
Sphere

Flat
Plate



Disc

Wedge



Cone

Slab



Rod

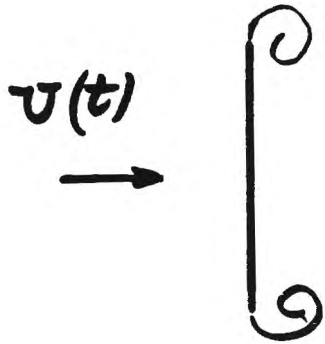
Vortex
Shedding

Shedding

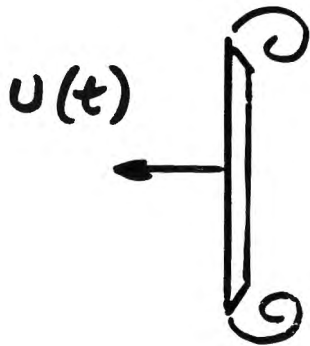
Quasi 2D

Not axisymmetric

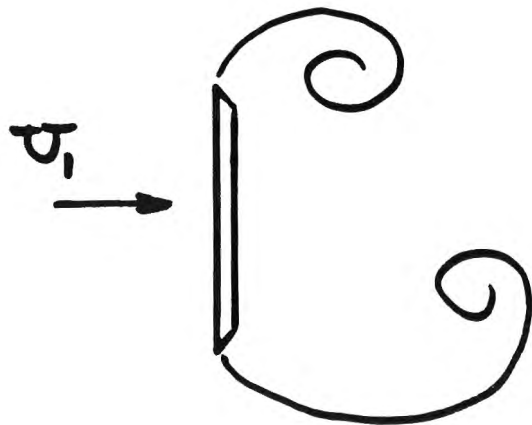
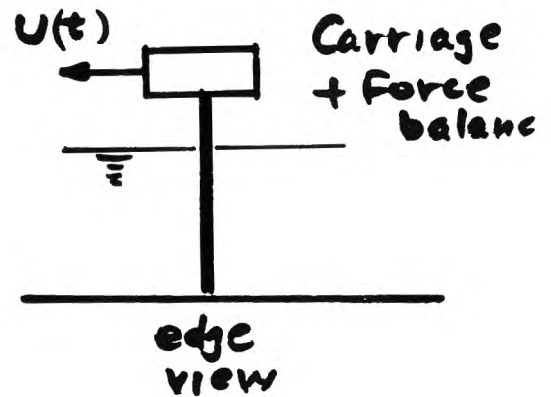
FLAT PLATE



Numerical Simulation
exactly 2D



Tow Tank
nominally
2D



Free-Surface
Water Tunnel

nominally
2D, "steady"

(Also DISC?)

3 Kinds of "2D" Flows

1. Exactly 2D

Realizable only in Numerical Simulation:
(cf soap-film "wind tunnel")

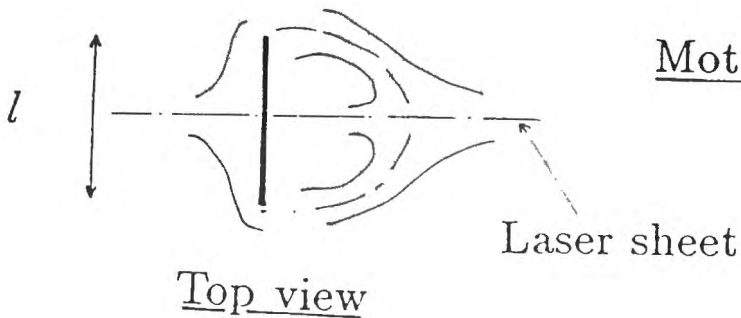
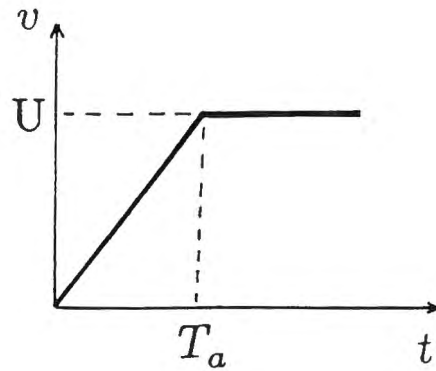
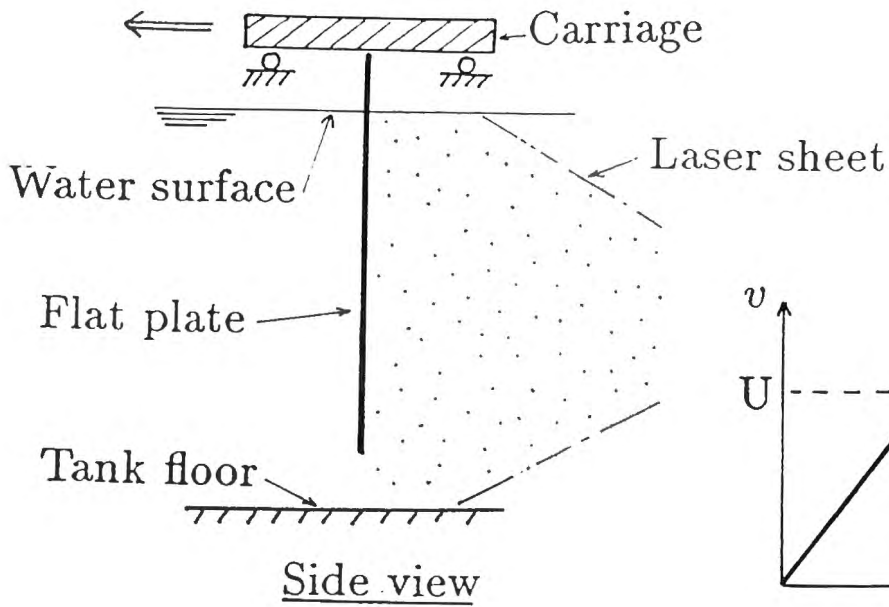
2. Real, Laboratory Flows

- End effects
- Intrinsic 3D (turbulent) motions from instability ($Re \geq 10^2$)

3. Idealized Real Flows

- Nominally $\bar{2D}$. Spanwise homogeneous?
- With intrinsic 3D motions
- No end effects
- These are the scientific objective.
- Degree of realizability?

FLOW ABOUT A 2-D FLAT PLATE



$$U = aT_a$$

$$T_a^* = T_a \sqrt{\frac{a}{l}}$$

$$Re_U = \frac{Ul}{\nu}$$

$$Re_a = \frac{l\sqrt{al}}{\nu}$$

$$t_U^* = t \frac{U}{l}$$

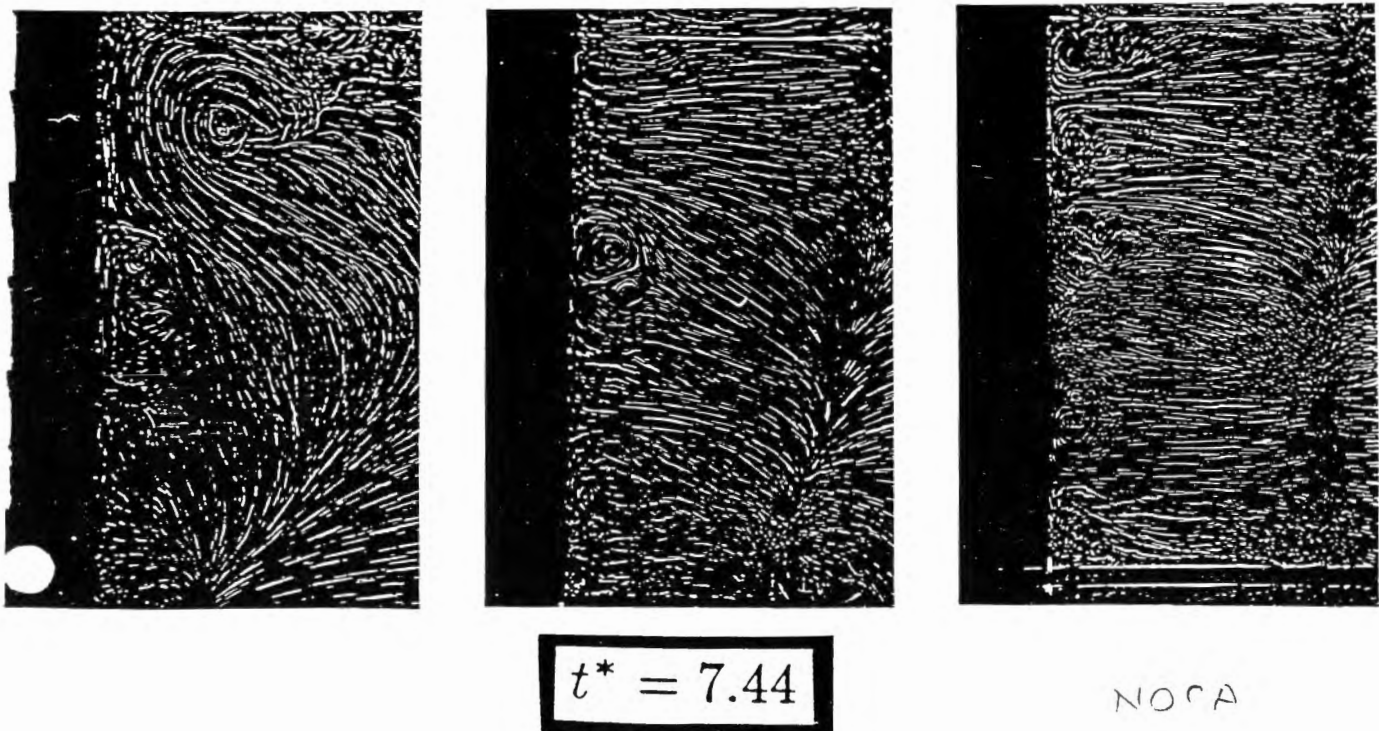
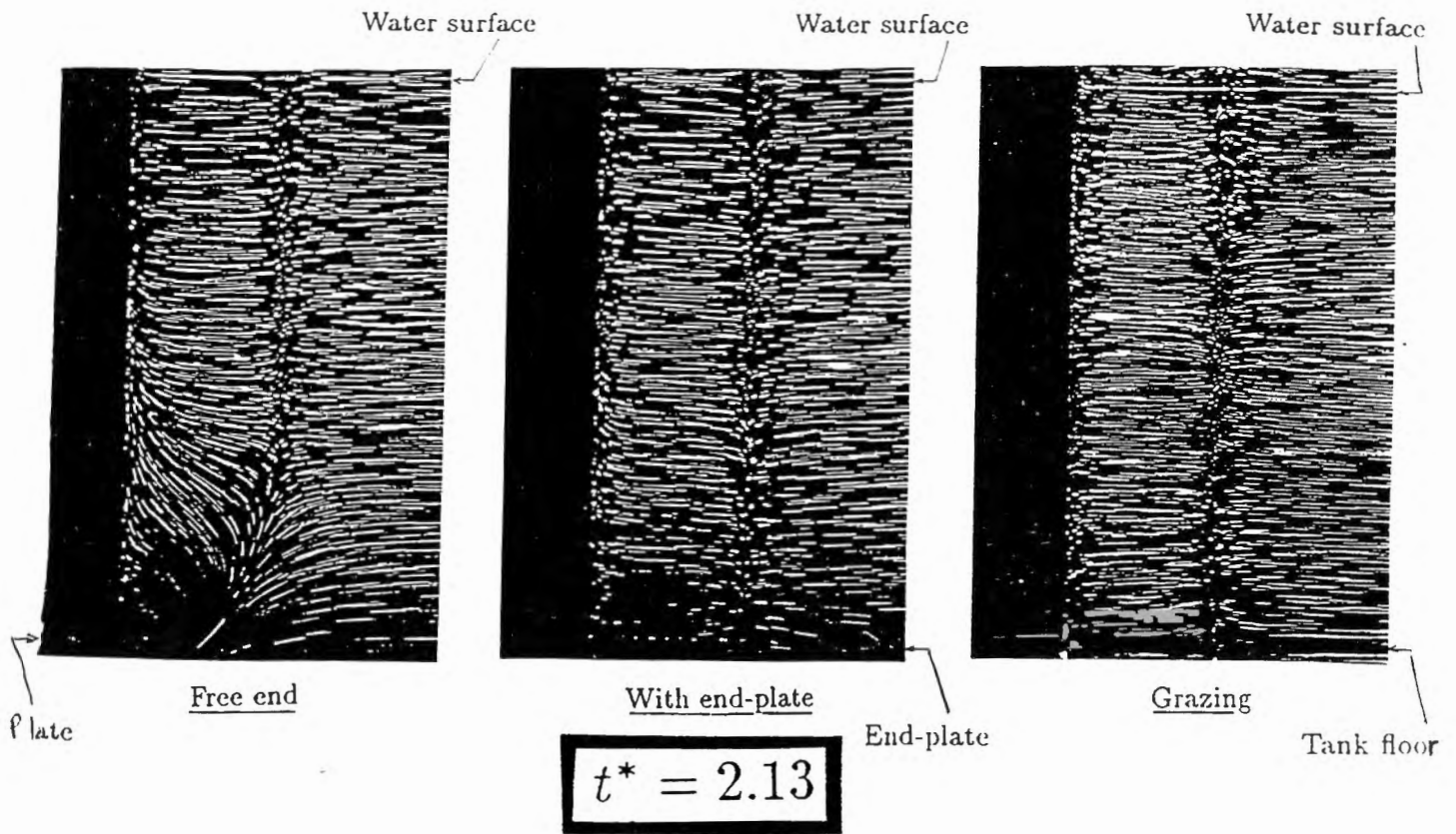
$$Re_a = 3966$$

$$Re_U = 6096$$

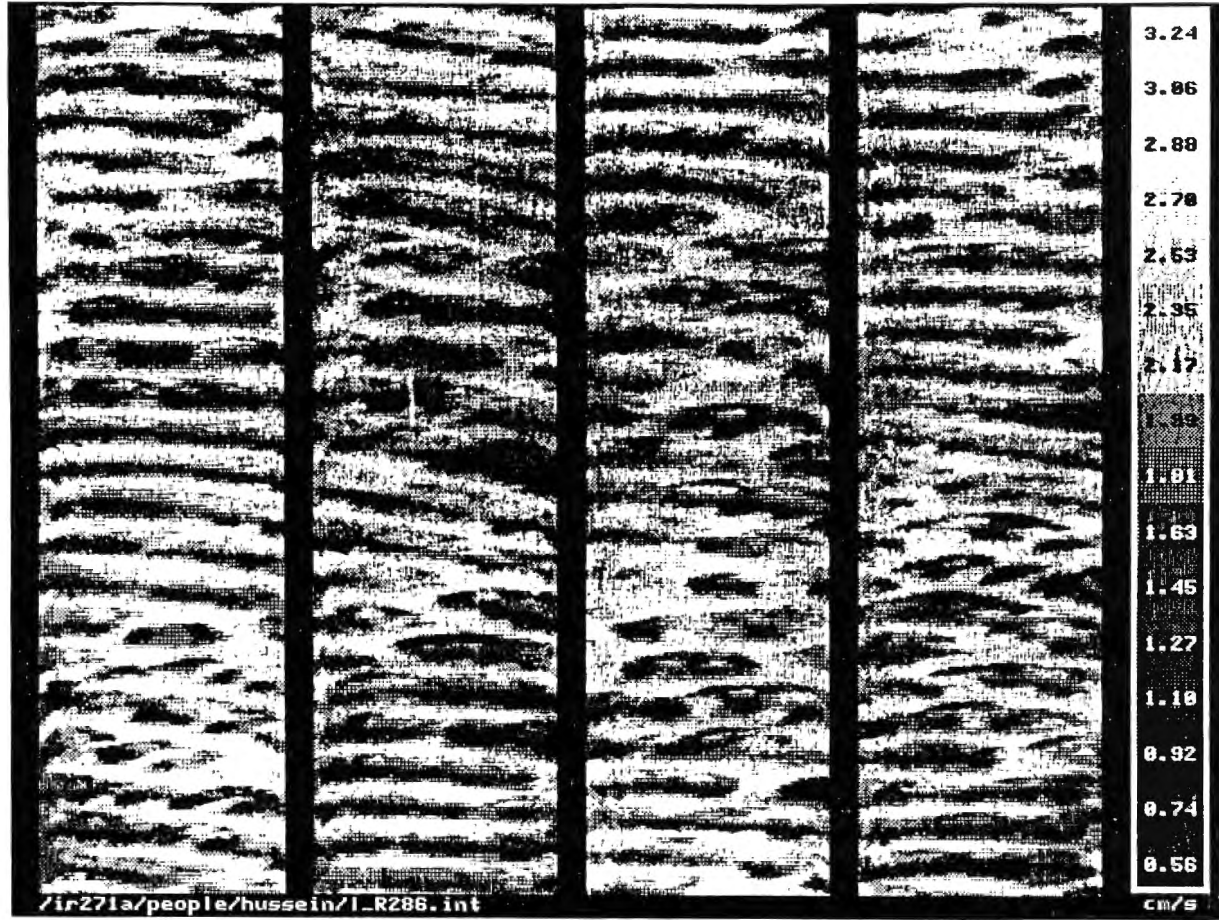
$$T_a^* = 1.54$$

Noca

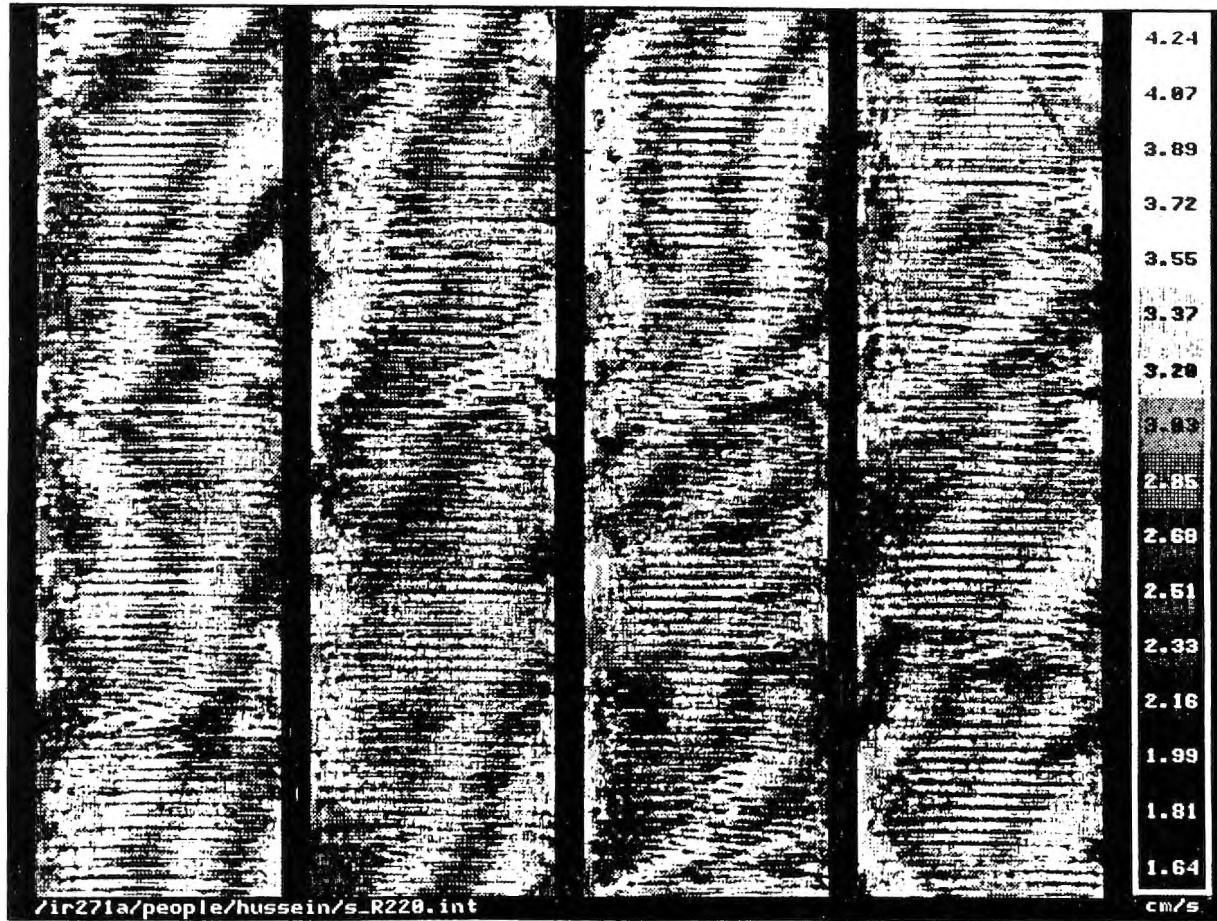
END EFFECTS ON THE FLOW PAST FLAT PLATES



D. Williams, L.I.T.

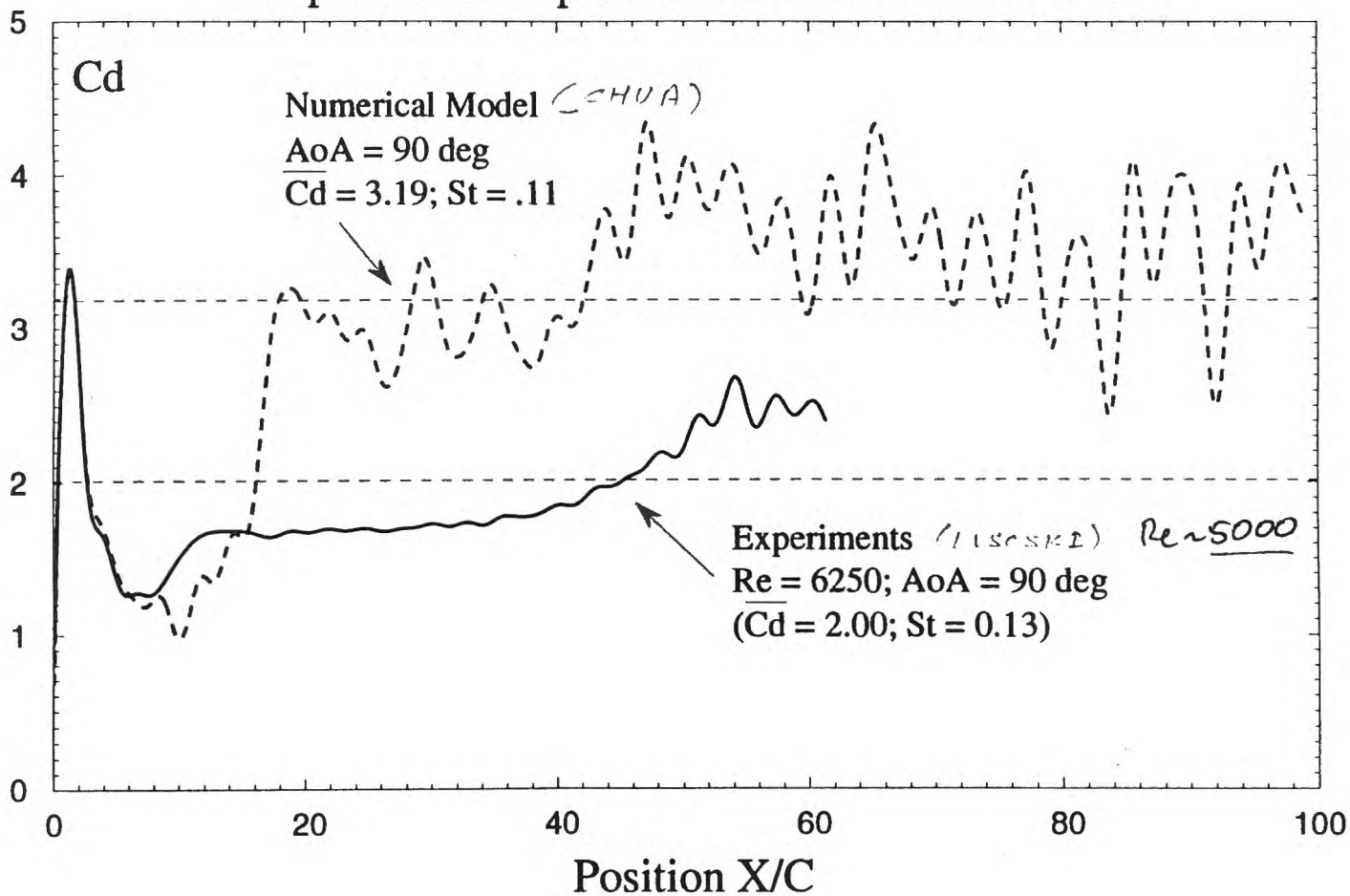


4-11



D. Williams I.I.T.

Comparison of Experiment and Numerical Model



\overline{Cd} from NUM
 up to $X/C \approx 400$

\overline{Cd} from FSMT

4-12

$c = 5 \text{ cm}$
 $t/c = 7\%$

XY-STAZINS
 FSMT- " false bottom

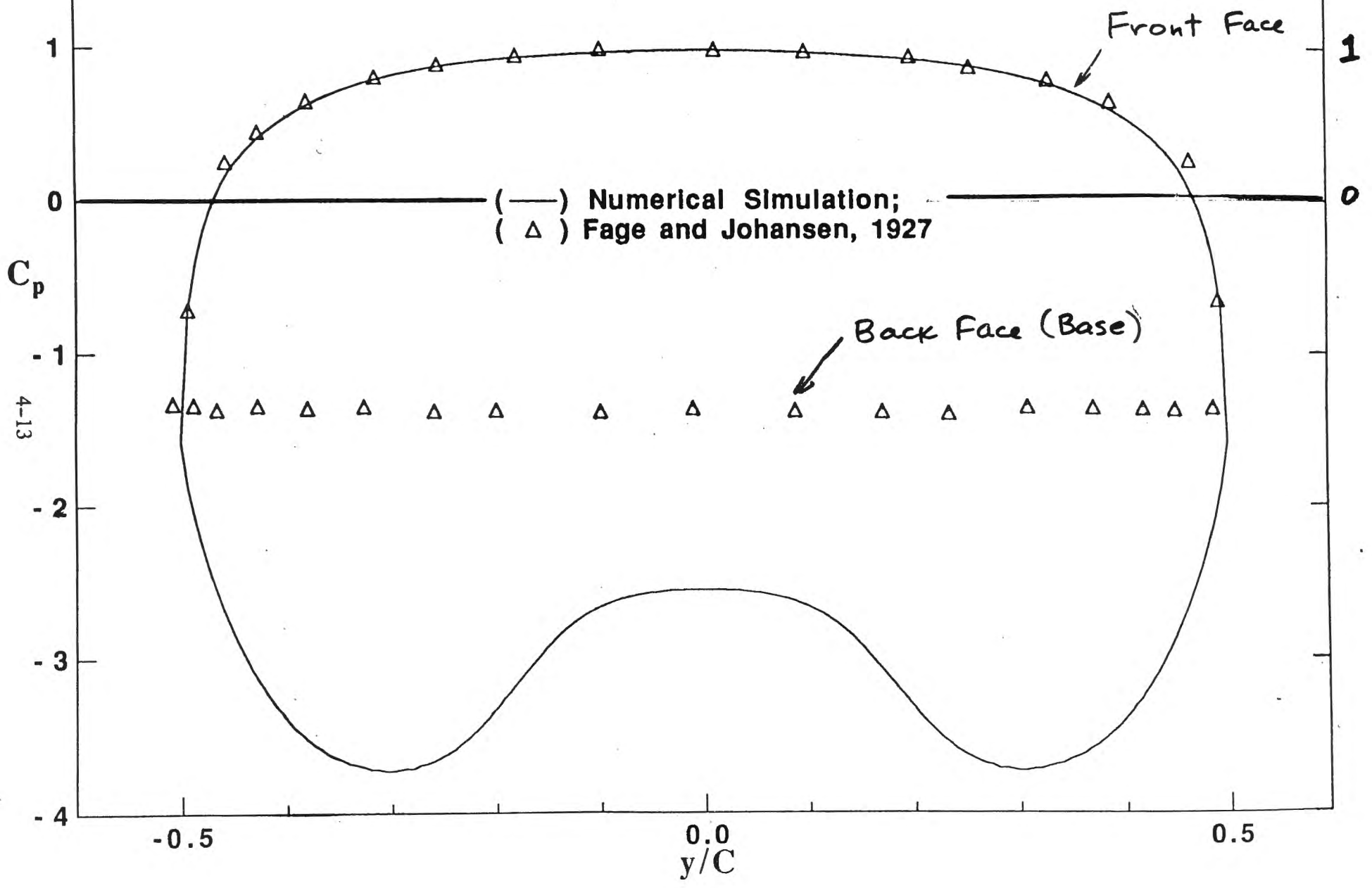
-0.5

0

0.5

y/C

Comparison of Numerical & Experimental C_p Distributions



C_p

4-13

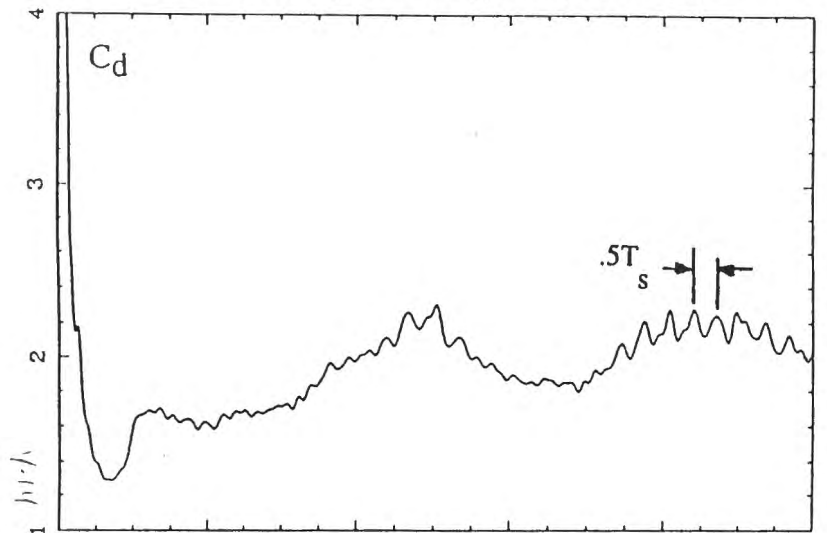
-0.5

0.0
 y/C

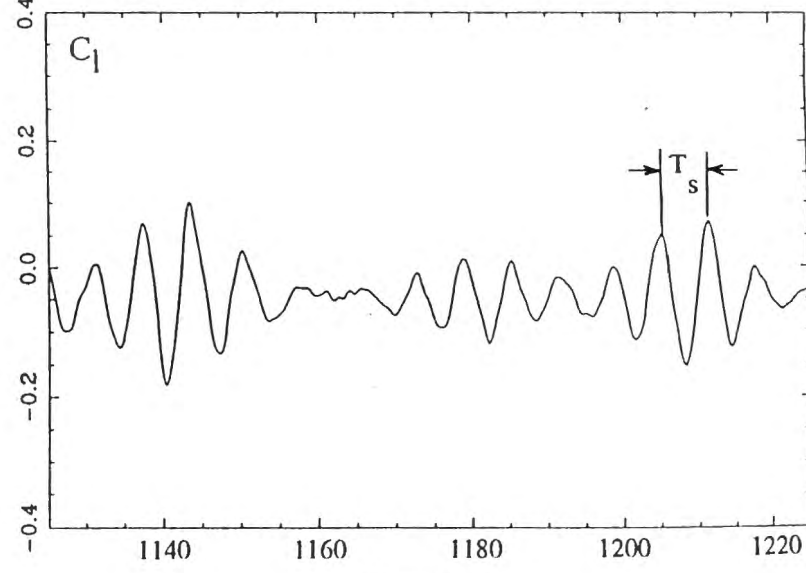
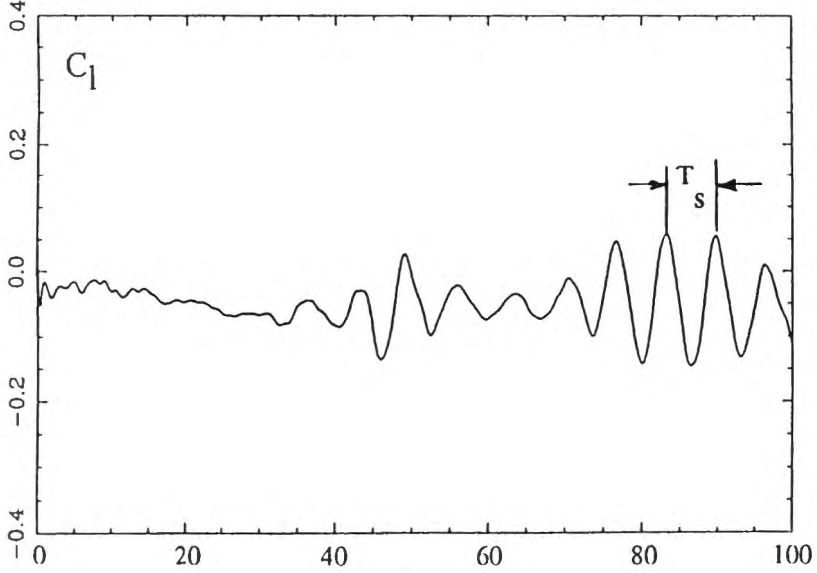
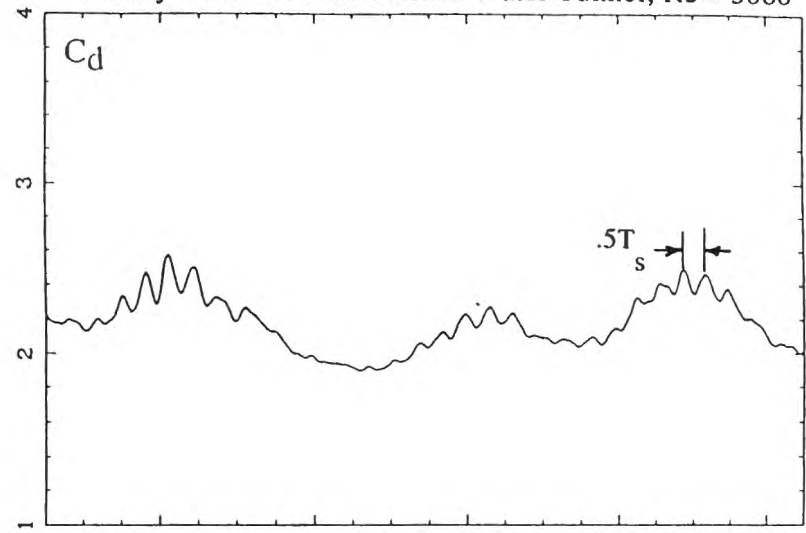
0.5

Force Histories On A Normal Blunt Plate

After Start-Up In Towing Tank; $Re = 3600$



"Steady-State" In Free Surface Water Tunnel; $Re = 3060$

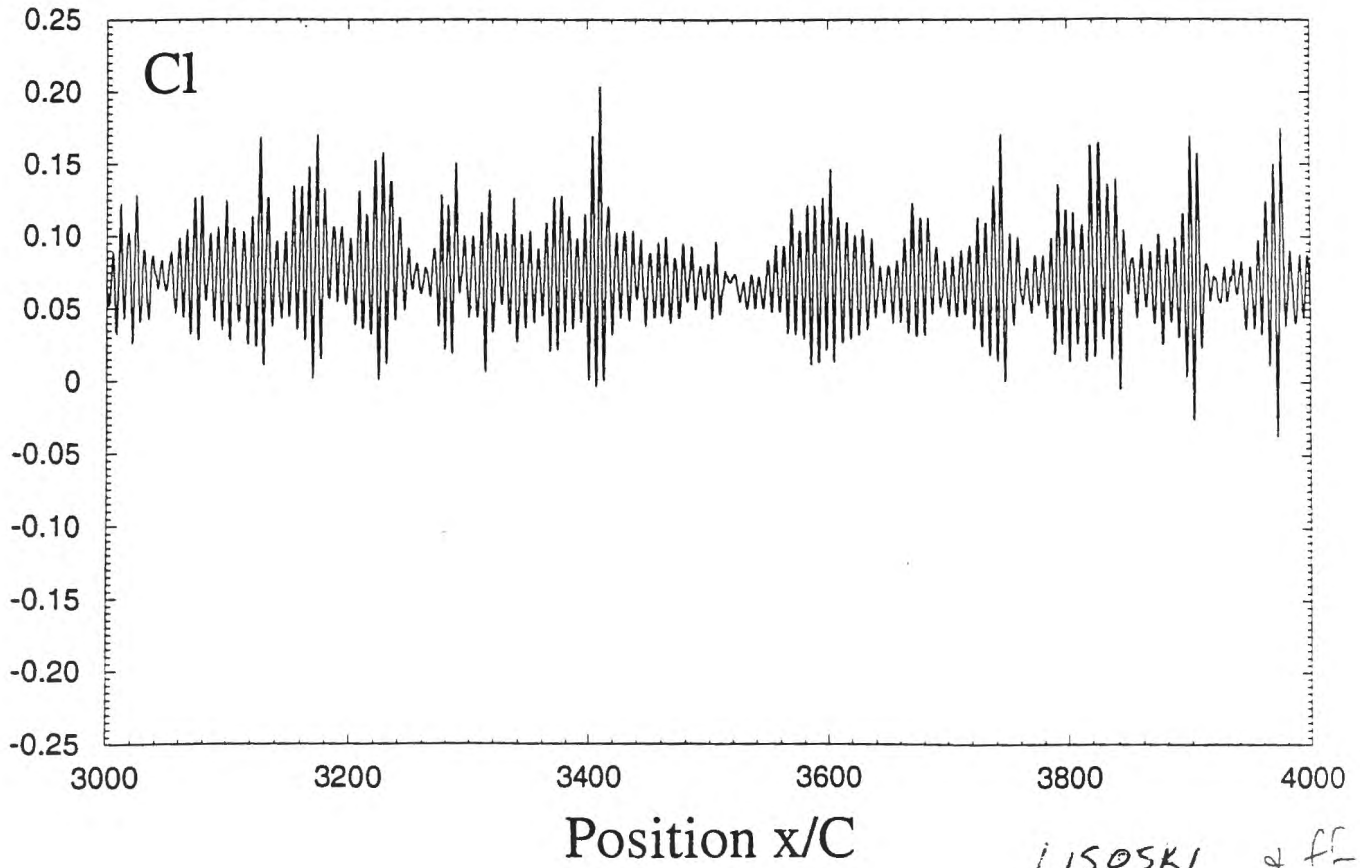
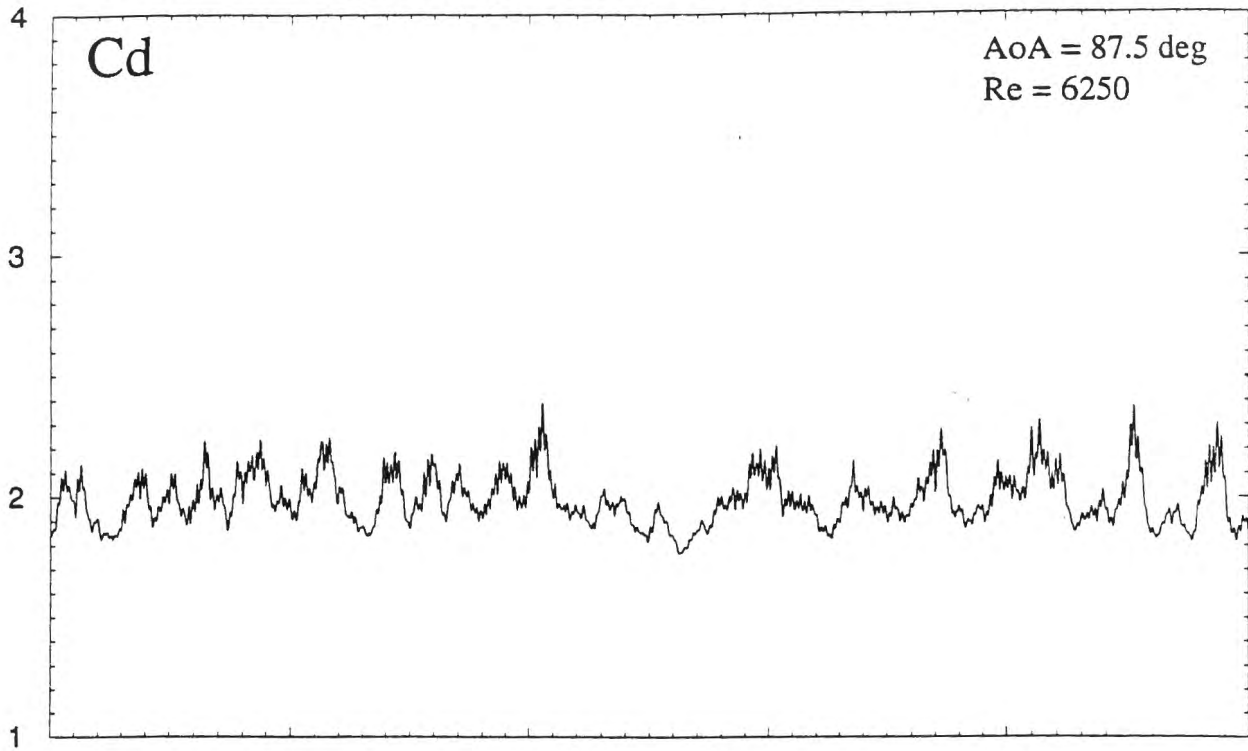


Position x/C

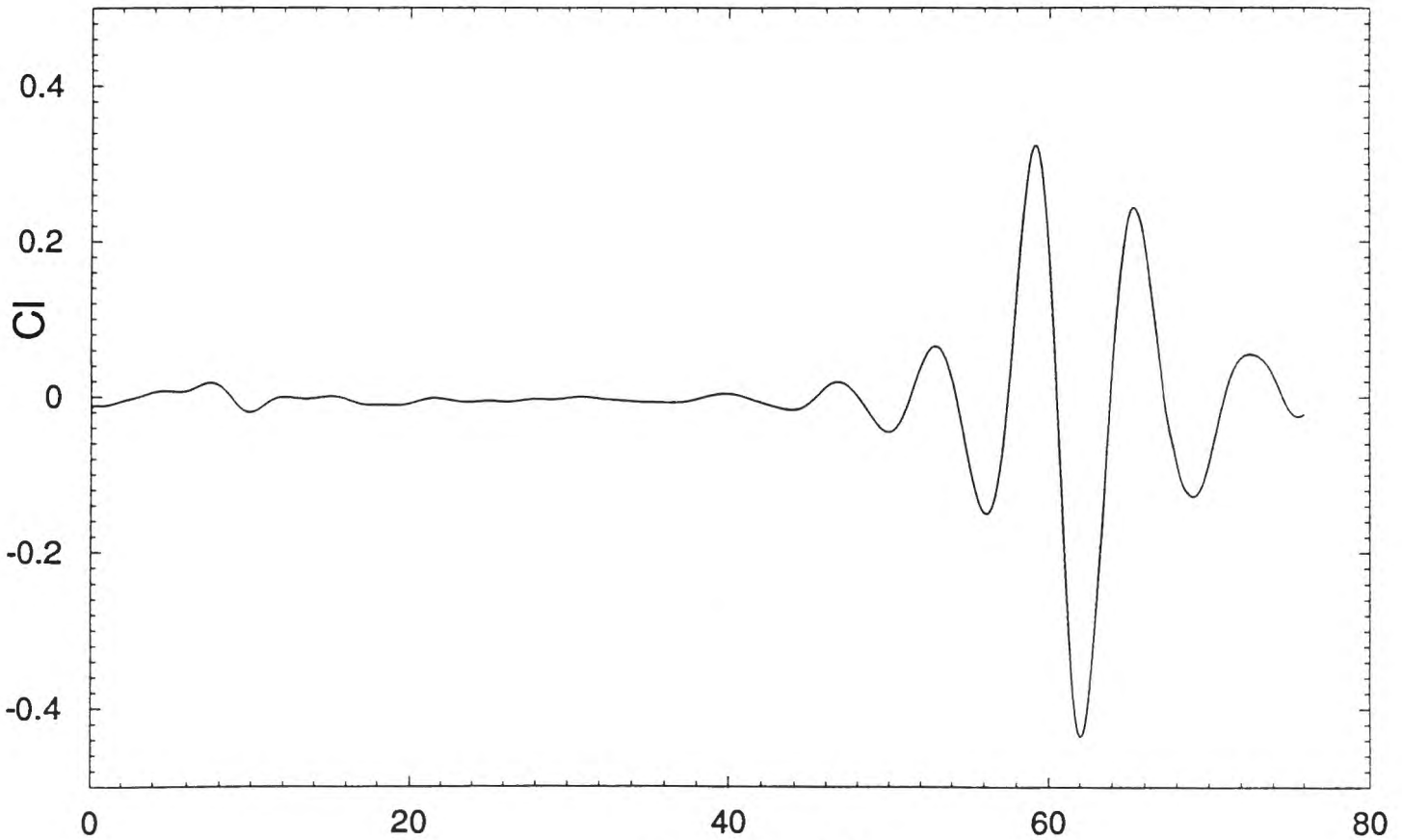
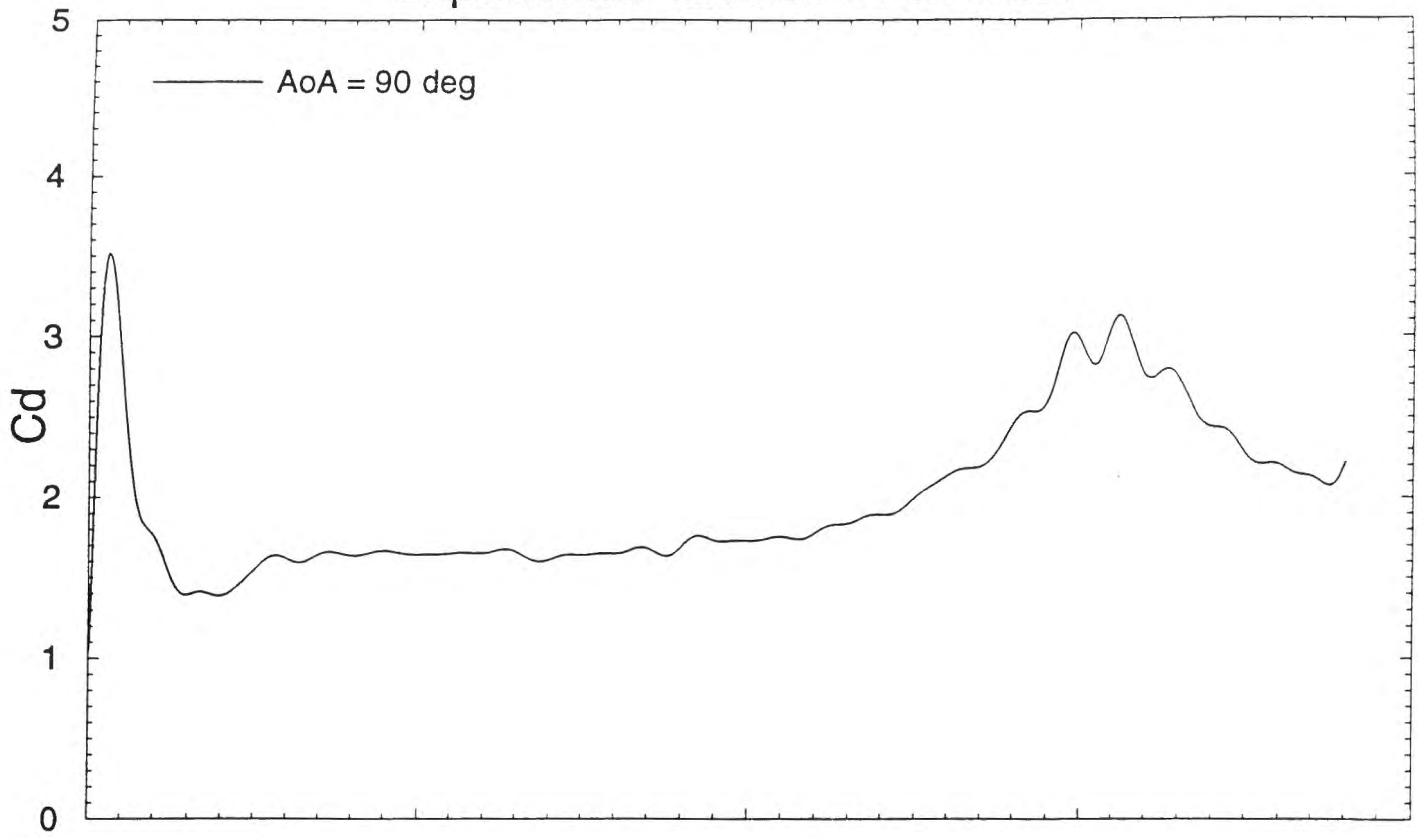
$x/C \equiv Ut/C$

$T_s \equiv$ Strouhal Period

Force Fluctuation - Free Surface Water Tunnel

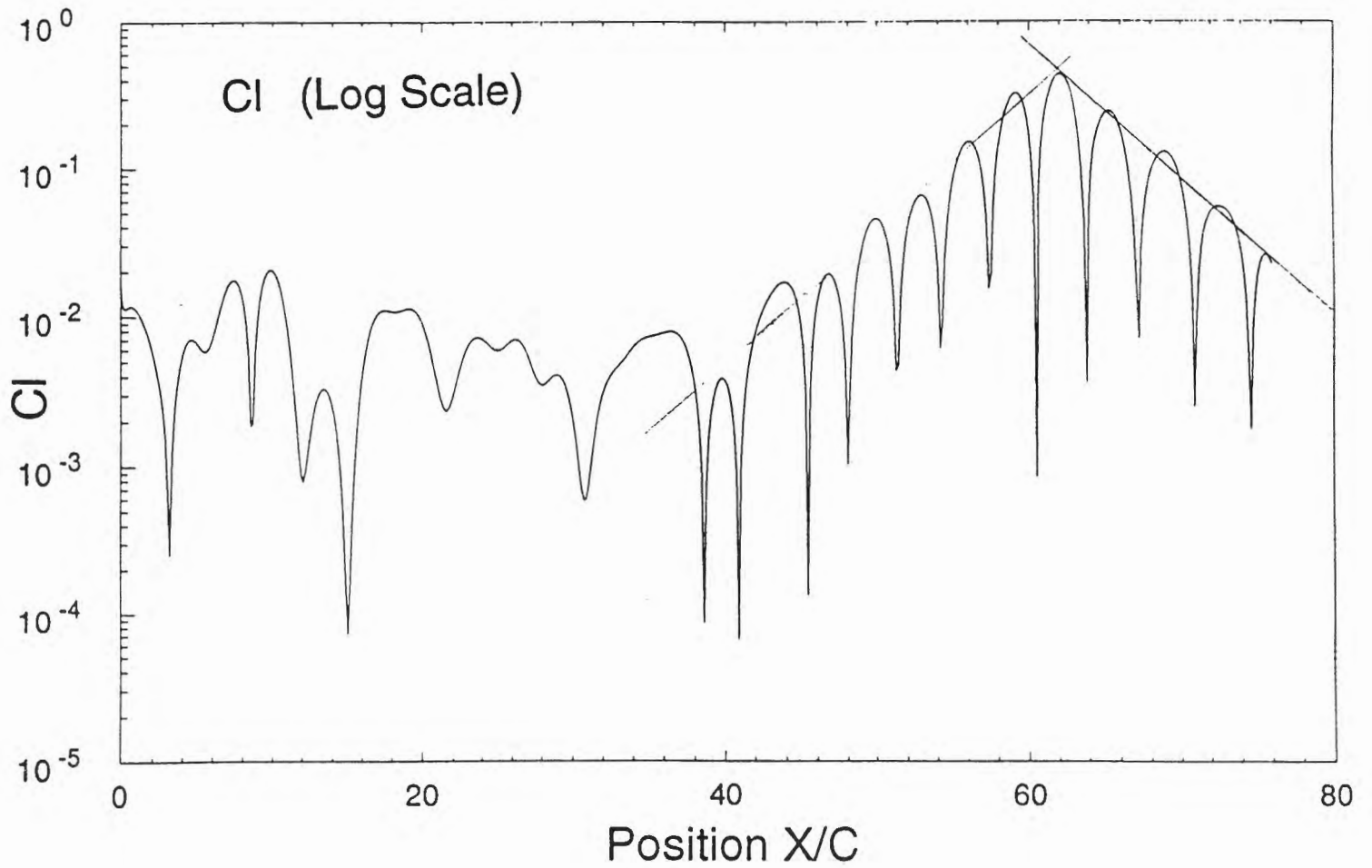
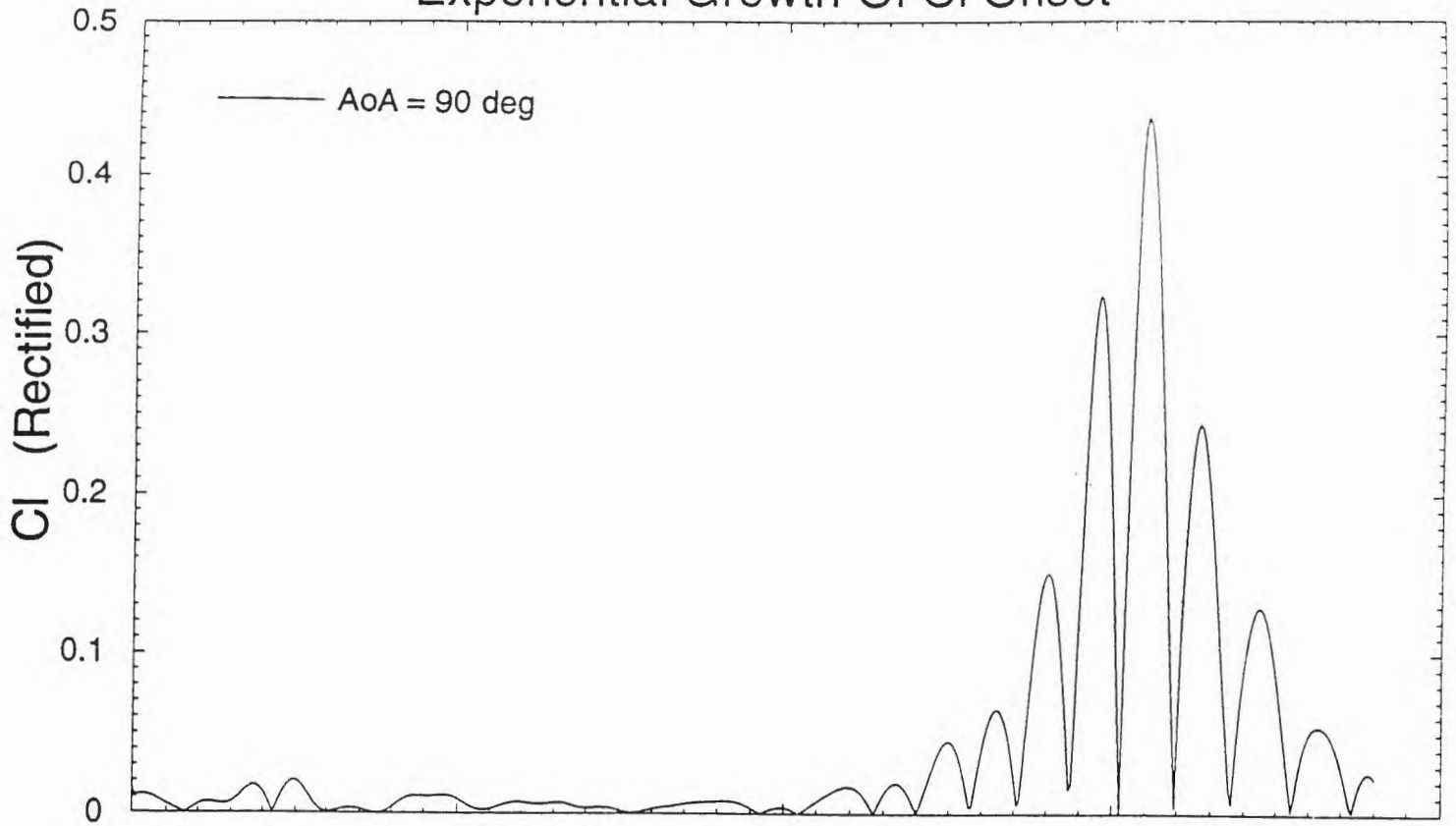


Exponential Growth Of Cl Onset

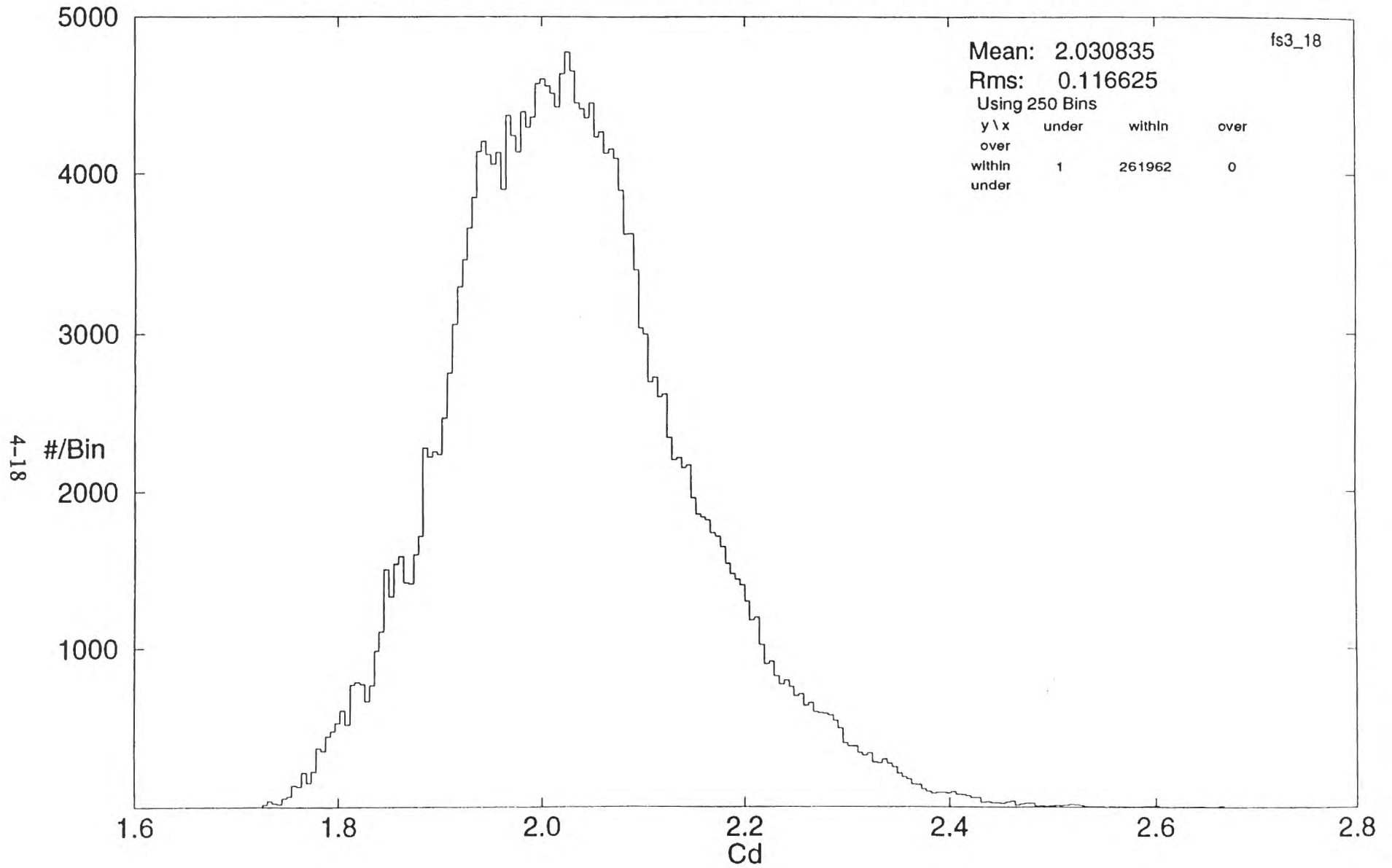


Position X/C

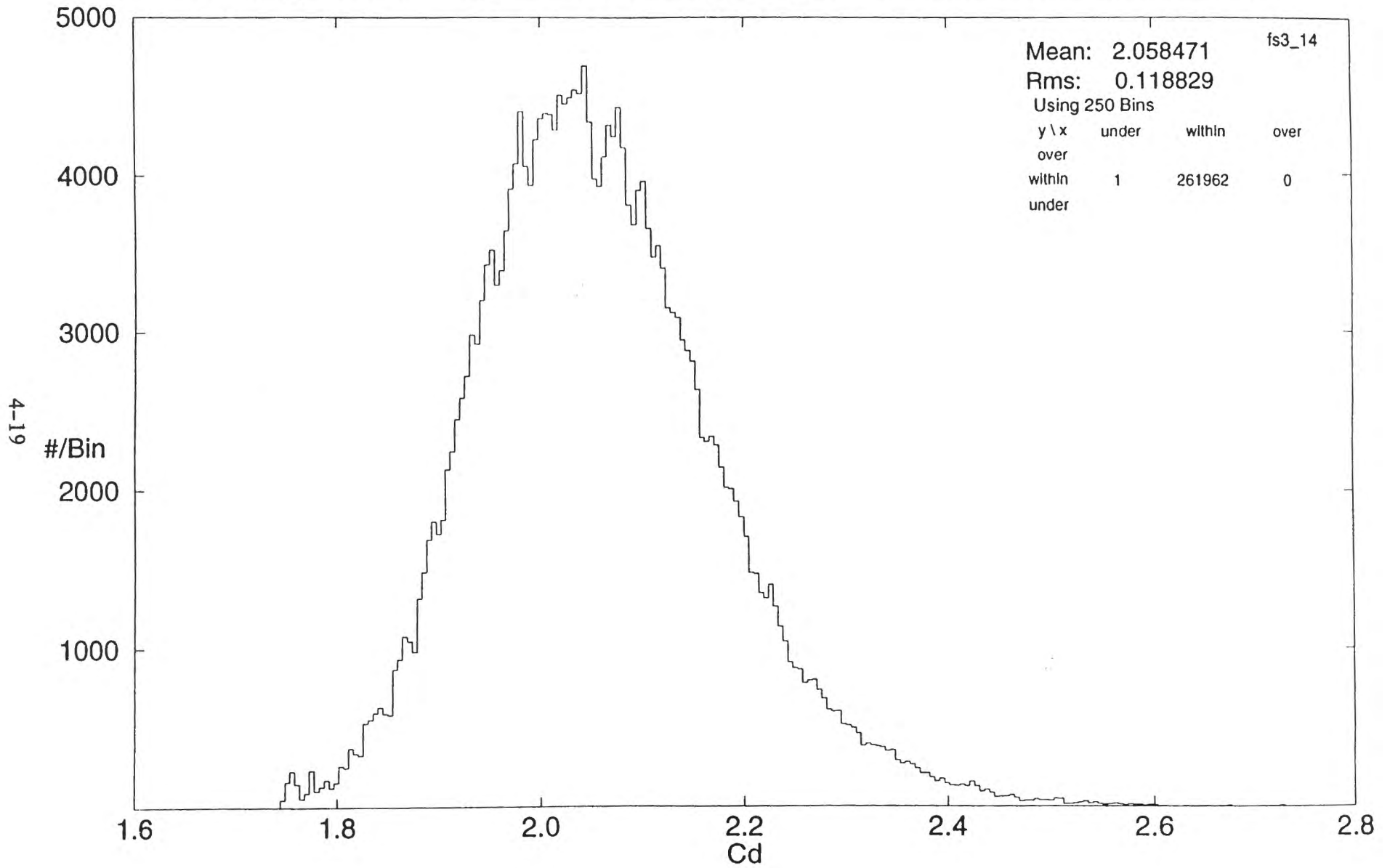
Exponential Growth Of CI Onset



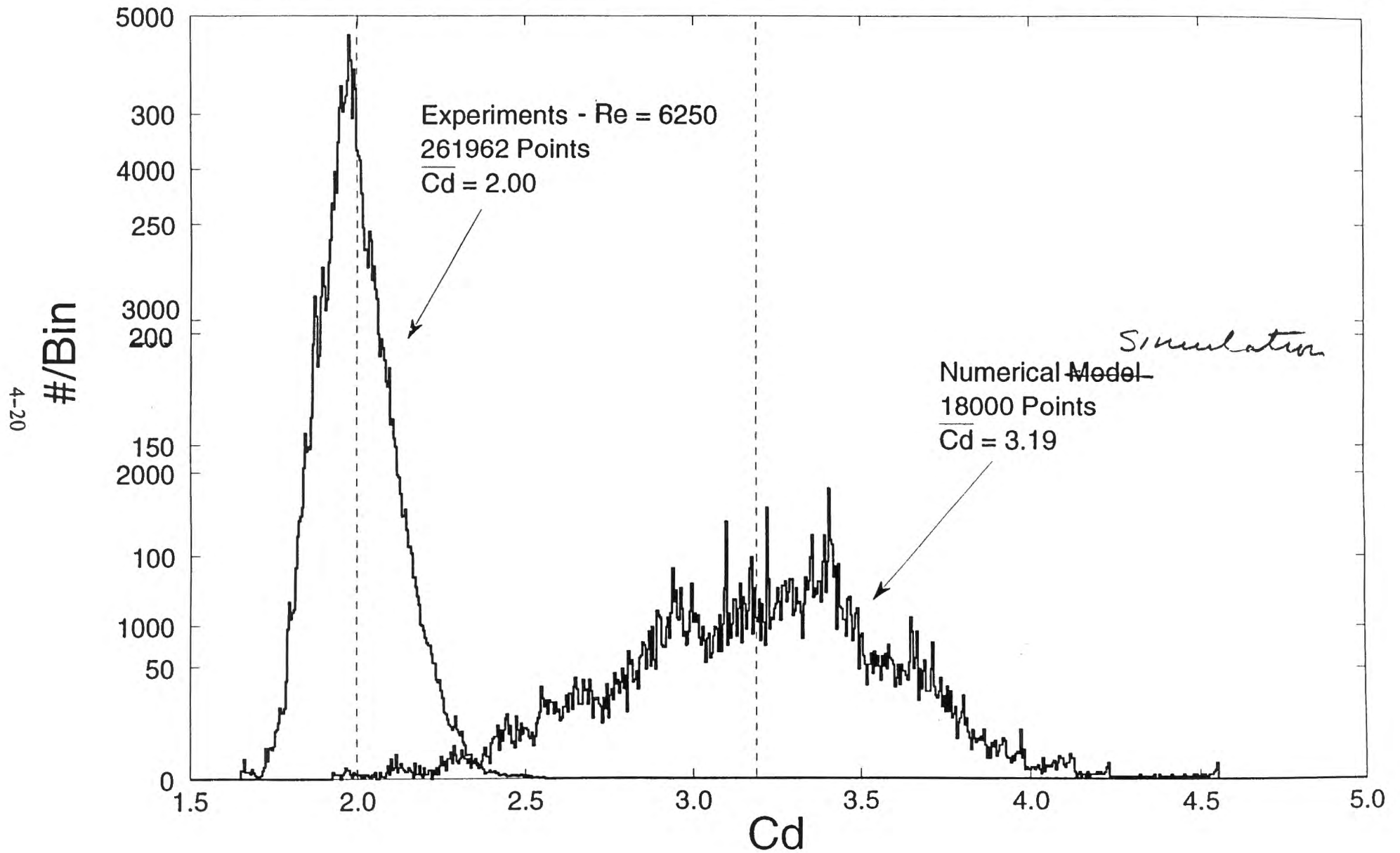
Histogram of Drag Coefficient Fluctuations in FSWT - $AoA = 85$



Histogram of Drag Coefficient Fluctuations in FSWT - AoA = 90

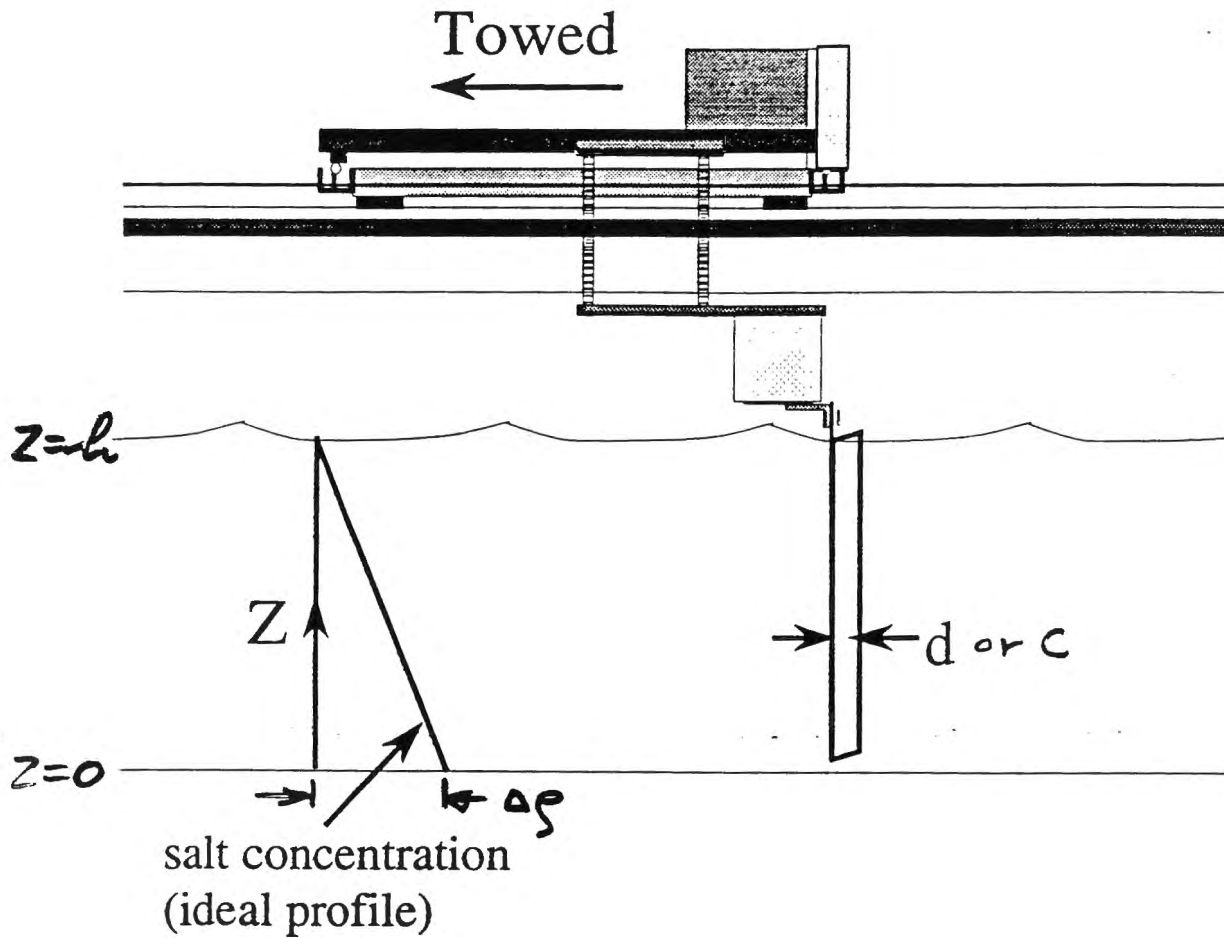


Histogram of Drag Coefficient Fluctuations - AoA = 87.5 deg



Density Stratification Experiments

- reduce 3-d turbulence by damping spanwise motions.



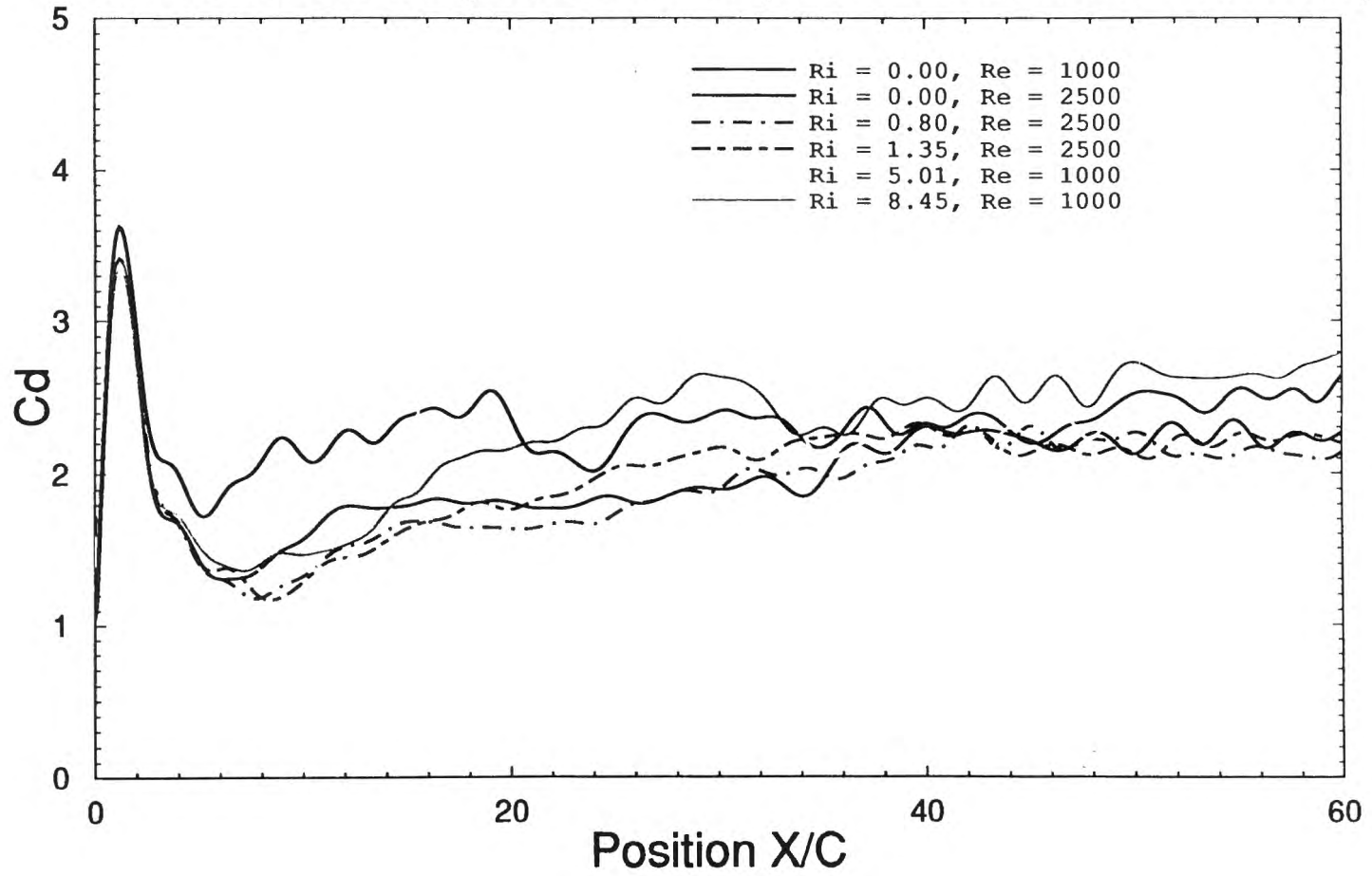
$$g \frac{d\rho}{dz} = \text{constant} \quad (\text{spanwise homogeneous})$$

Richardson Number: measure of effect of buoyancy

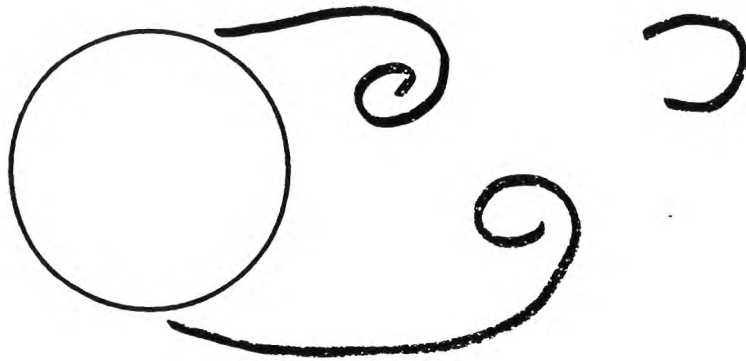
$$R_i = \frac{g \frac{d\rho}{dz}}{\rho \left(\frac{dw}{dz} \right)^2} = g \frac{\frac{\Delta\rho}{h}}{\rho \frac{U^2}{d^2}} = \frac{\Delta\rho}{\rho} \frac{g d}{U^2} \frac{d}{h}$$

$$R_i = \frac{\Delta\rho}{\rho} \frac{g}{h} \frac{d^2}{U^2}$$

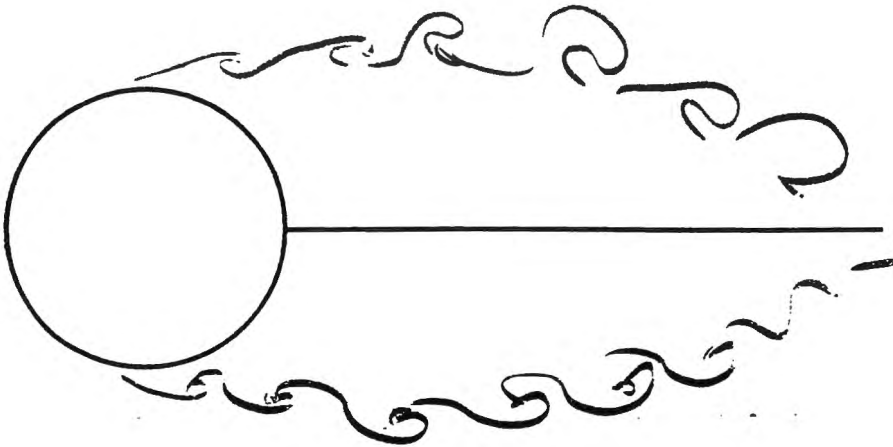
Stratification Effects (Small End Gap, $C = 5\text{cm}$, $\text{AoA} = 90.0\text{ deg}$)



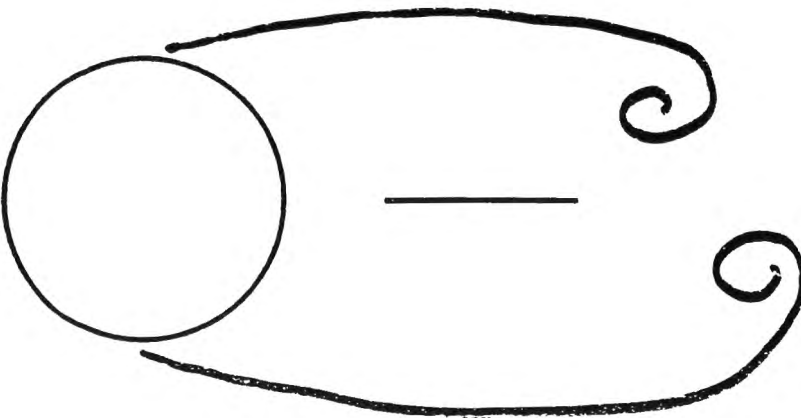
Interference Experiments
on
NEAR-WAKE DYNAMICS



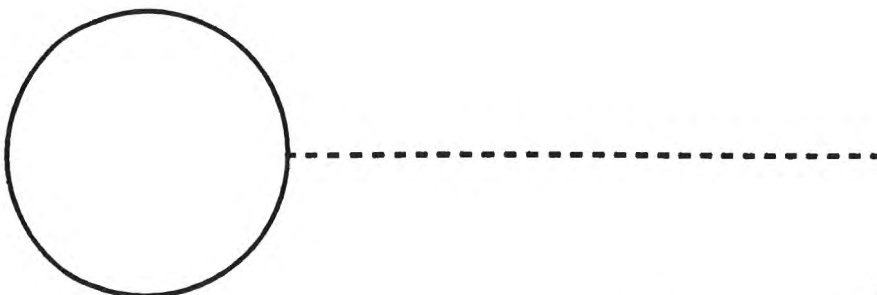
Open Wake



Long
Splitter
Plate



Short
Splitter
Plate



Splitter Screen

$\sigma \equiv$ Solidity Ratio

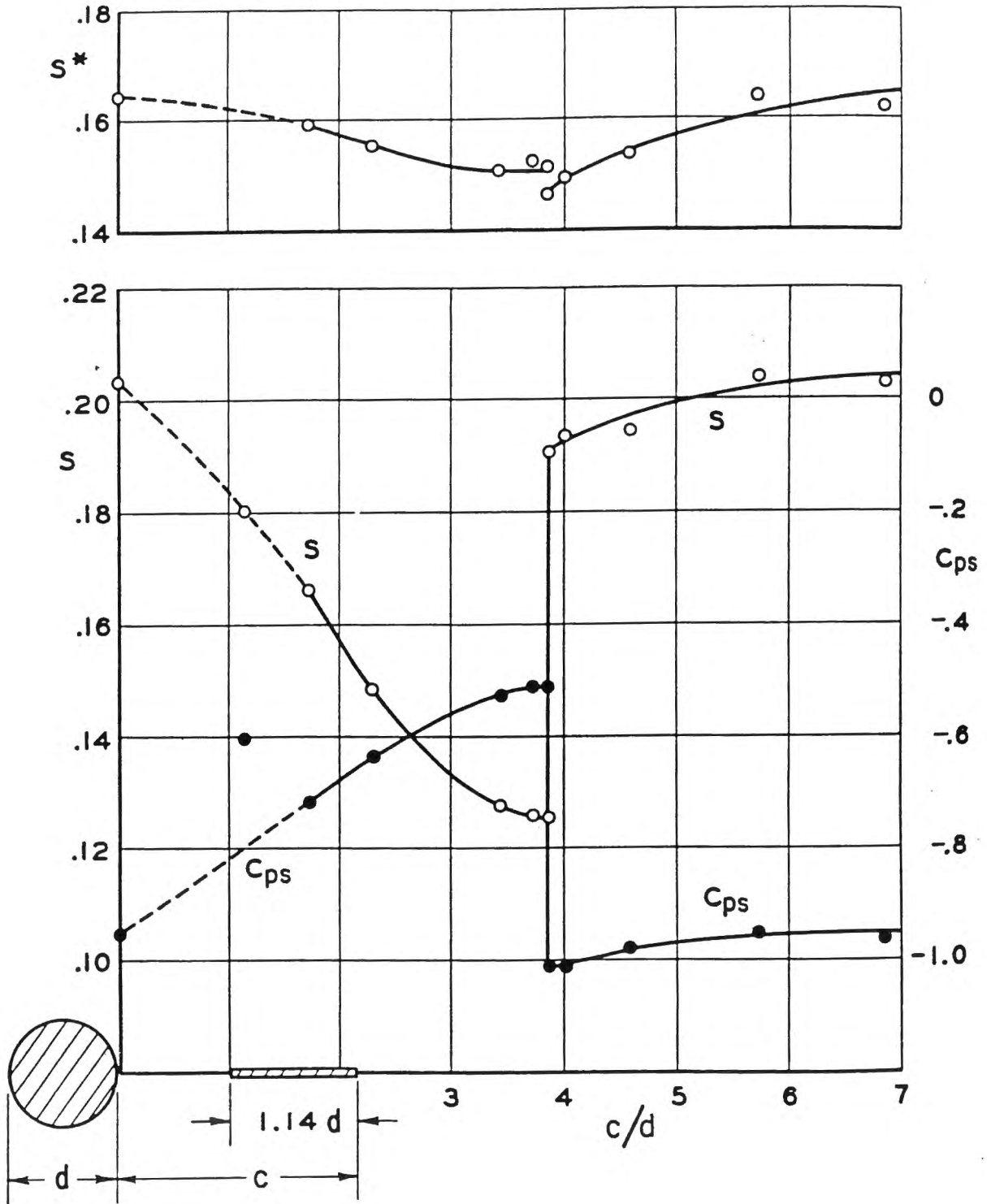
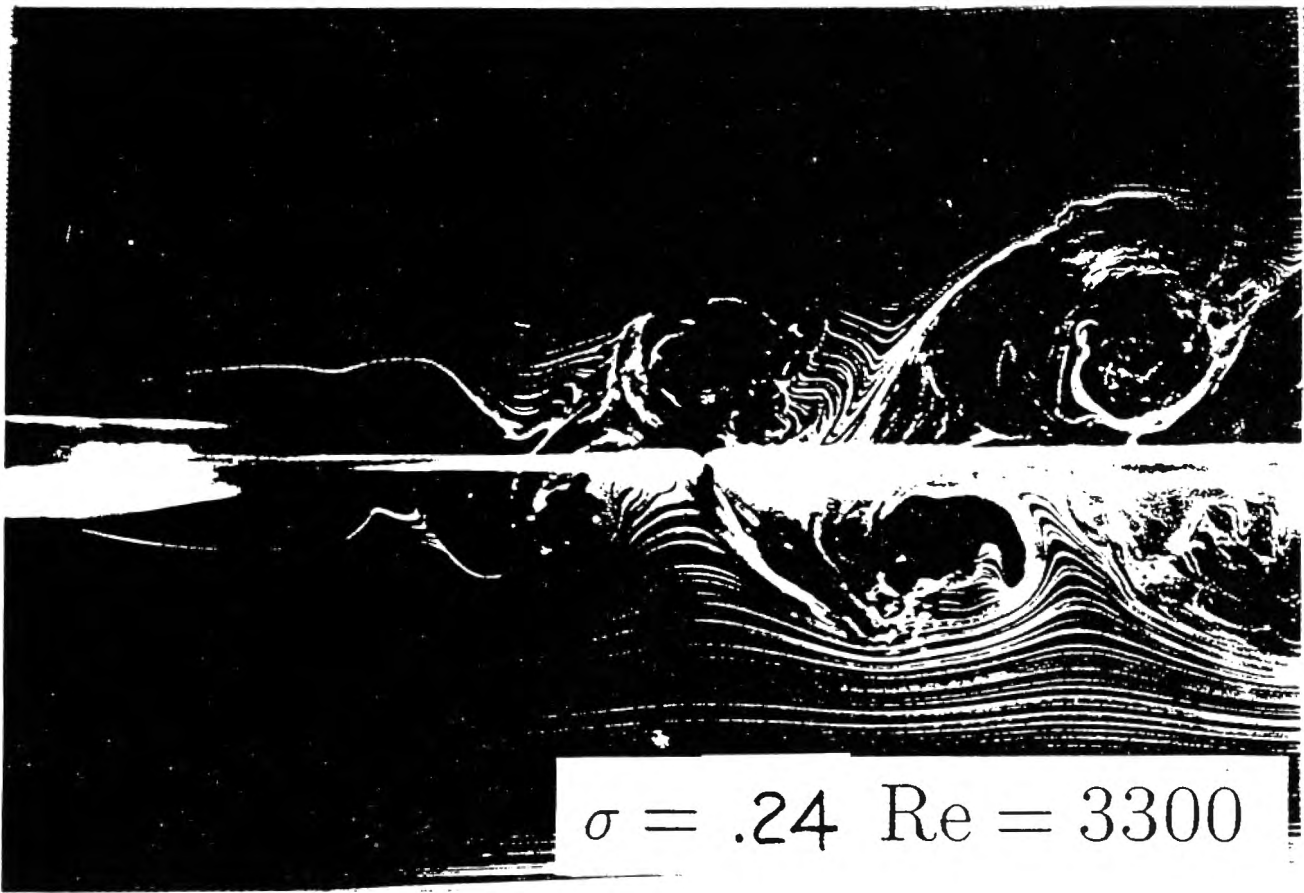
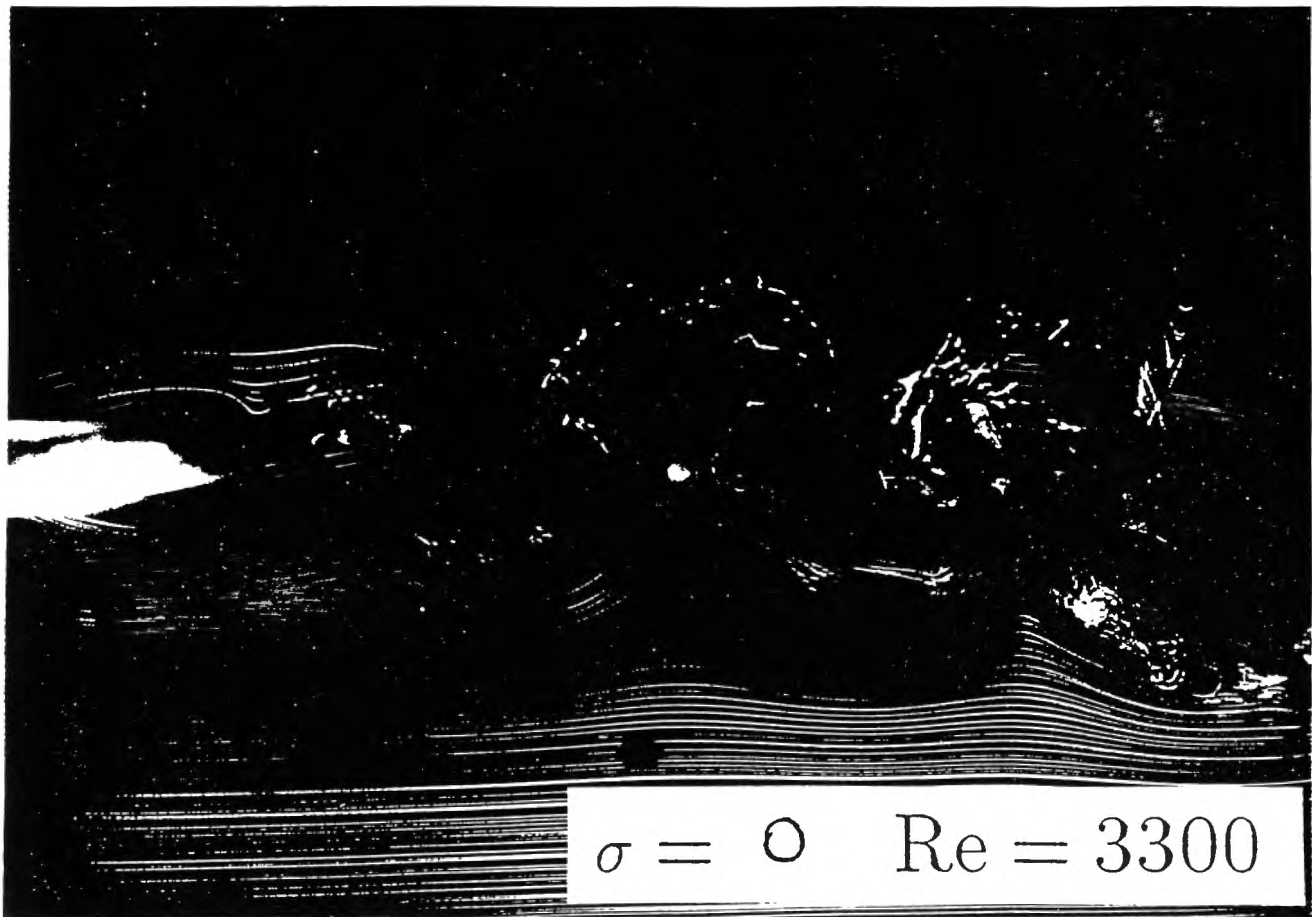


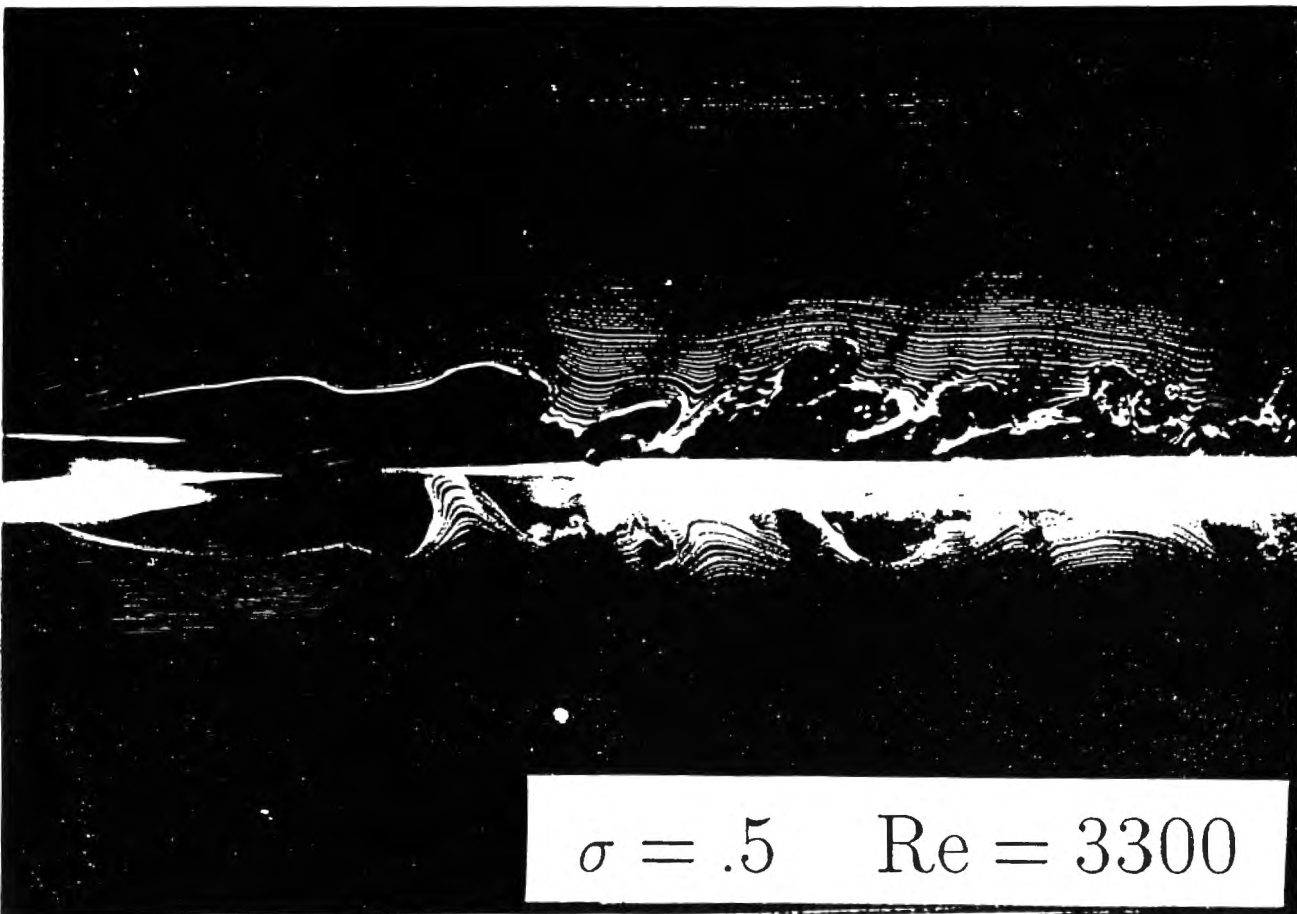
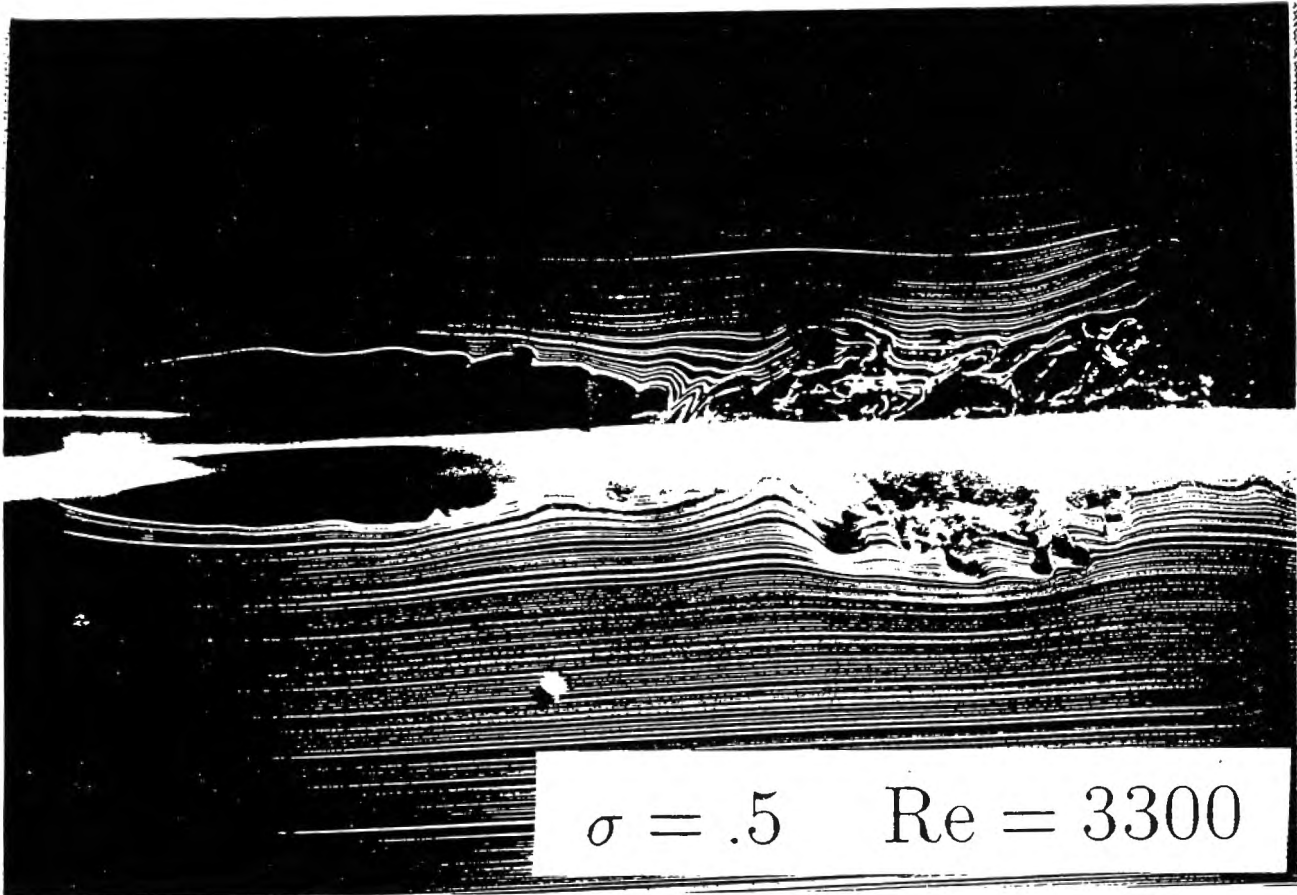
Figure 4.- Wake interference.

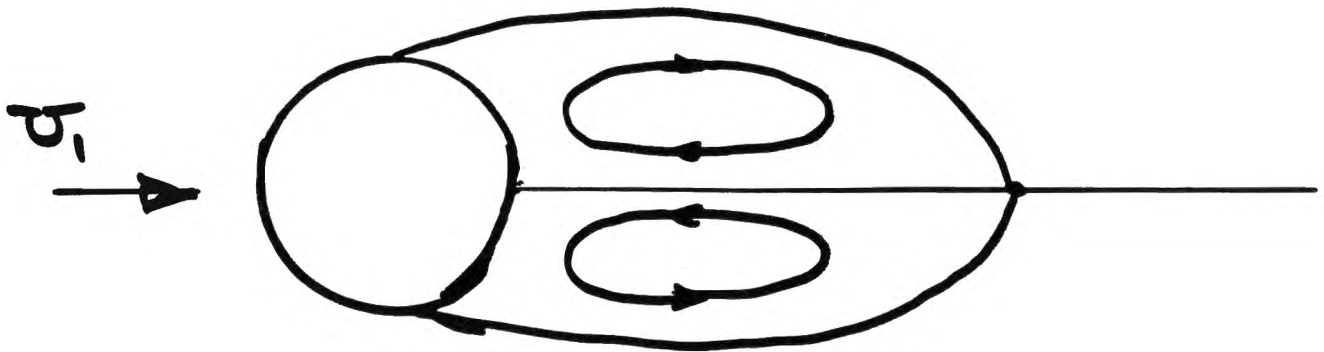


$\sigma = .24$ Re = 3300



$\sigma = 0$ Re = 3300





Mean Flow Field.

Described by Reynolds' Equations

("time-averaged

Navier-Stokes modelling")

(Effect of splitter plate?)

TURBULENT VELOCITY FIELD :

$$u_i(x_j, t) = \bar{u}_i(x_j) + u_i'(x_j, t)$$

Navier-Stokes Equations

continuity $\frac{\partial u_k}{\partial x_k} = 0$ incompressible

momentum $\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \tau_{ij}$

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad \begin{array}{l} \text{CLOSURE} \\ \text{(Newtonian Fluid)} \end{array}$$

Reynold's Averaged Equations (\bar{R} equations)

$$\frac{\partial \bar{u}_k}{\partial x_k} = 0$$

$$\frac{D \bar{u}_i}{Dt} = \rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} (\bar{\tau}_{ij} + \tau_{ij})$$

$$\tau_{ij} \equiv \rho (-\overline{u_i' u_j'})$$

PROBLEM
OF
CLOSURE

TRADITIONAL METHODS : (velocity field)

- Reynolds-averaged (\bar{Re}) modelling
 - Shear Flows -one-point correlations, e.g. $\overline{u'v'}$, $\overline{u'p'}$, etc.

- Statistical Theory

- Homogeneous Flows -

two-point correlation functions, e.g.

$$\overline{u'(x,t) u'(x+r, t+\tau)} = f(r, \tau) \overline{u'^2}$$

spectra

MODERN APPROACH : (vorticity field)

Incorporate

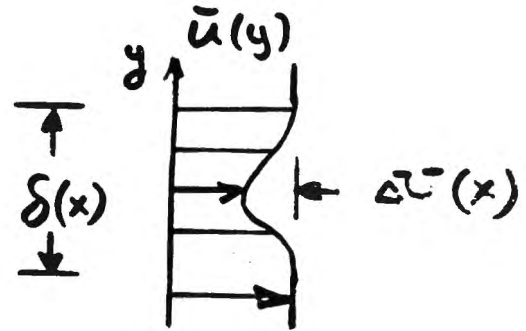
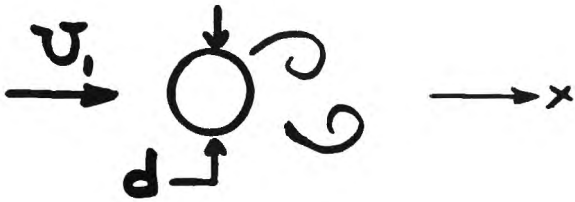
- Describe "organized", "coherent" vortical structures and their interactions before doing the statistics.

How?

What are they doing? : They are a manifestation of the underlying physics.

Near & Far Fields of Free Shear Flows

Cylinder Wake



"Near Wake" ($x \leq 5d$)

Wake Oscillation,
Vortex "Shedding".

Initial, fixed scales

$$U_i, d$$

$$f_K \approx 0.2 \frac{U_i}{d}$$

sharp spectrum

"Far Wake" ($x \geq 50d$)

Evolving Scales

$$\Delta U(x), \delta(x)$$

$$f_m(x) \sim 0.2 \frac{U_i}{\delta(x)}$$

broad spectrum

"Fully developed turbulence"

Primary Instability:

"Absolute"

Fixed

Primary Instability:

"Convective"

* Intermittent
(wave packet)

IMPLICATIONS AND USES OF COHERENT STRUCTURES

(ideas not accessible from traditional approaches)

- Role of global (primary) instability
 - characteristic for each shear flow
 - (implications for universal \overline{Re} models?)
- Rational explanation and correlation of parametric effects:
 - velocity ratio U_2/U_1
 - density ratio ρ_2/ρ_1
 - compressibility M_1, M_2
 - entrainment parameters
- Sensitivity to perturbation
 - uniqueness (Wynanski and Oster)
 - self-excitation? (Corcos and Kaul)
- Controllability
- Lagrangian view useful or necessary
 - e.g. coherent structure as a stirred reactor
 - (Broadwell)
- Closed models (Morris, Liu)
 - with $\rho u'v'$ from instability equations

Velocity

Vorticity

Vortex Sheets

Vortex Blobs

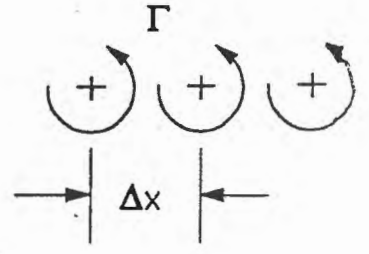
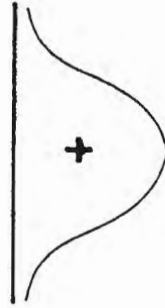
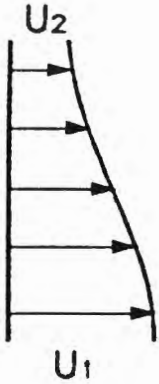
$\bar{U}(y)$

$-\frac{dU}{dy} = \bar{\Omega}(y;x)$

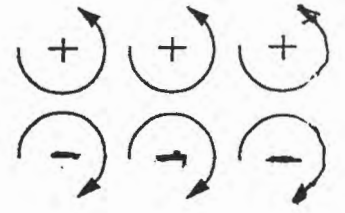
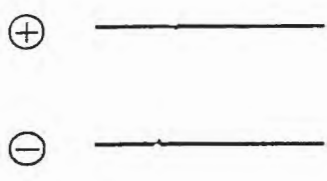
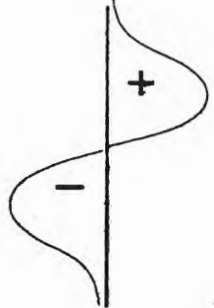
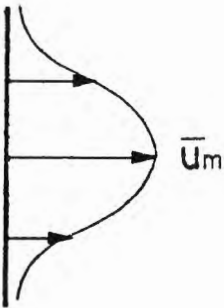
$\gamma(x) = \int \bar{\Omega} dy$
 $= U_1 - U_2$

$\Gamma = \gamma(x) \Delta x$

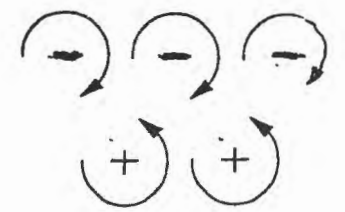
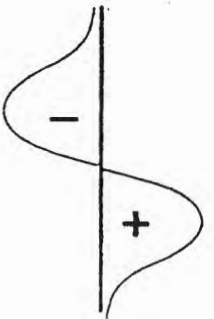
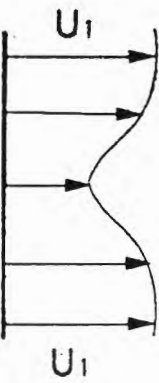
Mixing Layer



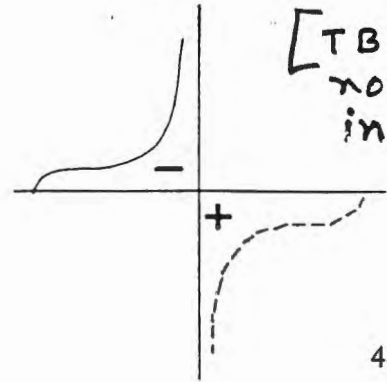
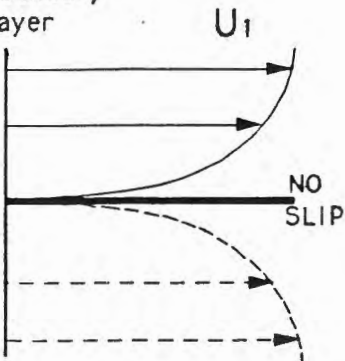
Plane Jet



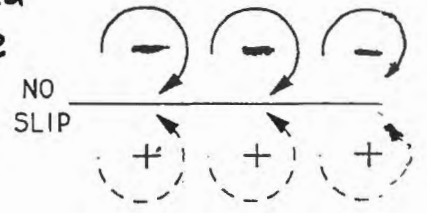
Plane Wake



Boundary Layer

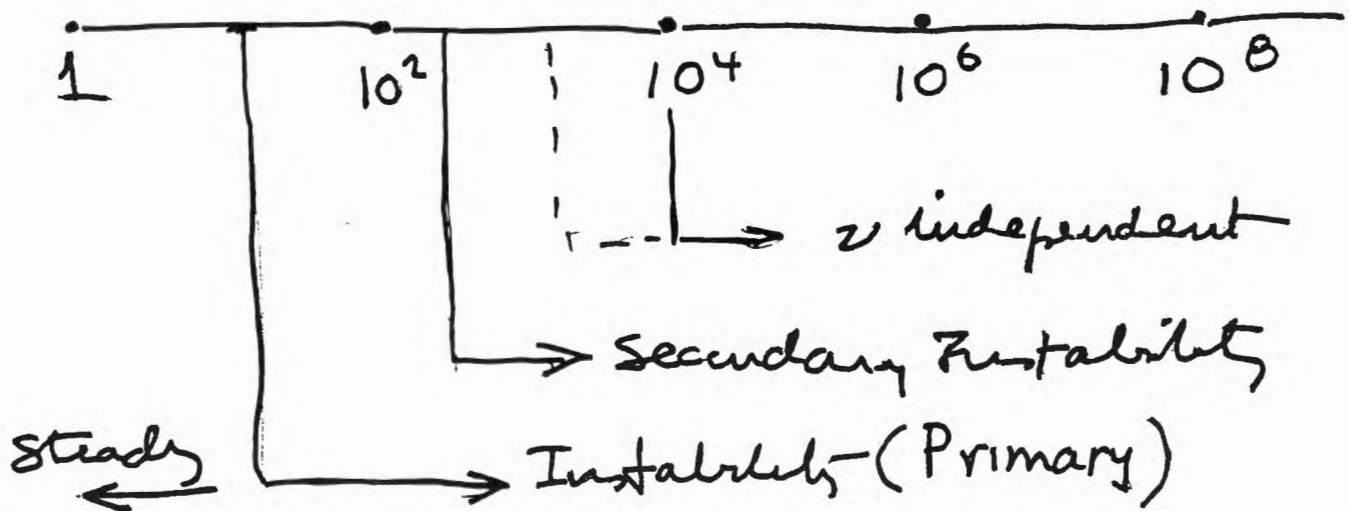


[TBL Large structures can not be derived in the same way]



Reynolds-Number Regimes for Free Shear Flows

$$Re \equiv \frac{UL}{\nu}$$



APPENDIX
INFORMATION ON SEMINAR SPEAKERS

ABBREVIATED VITAE

FAZLE HUSSAIN

CITIZENSHIP United States

EDUCATION Ph.D. (1969) & M.S. (1966) Stanford U.; B.S. (1963) Bangladesh U. (all in Mech. Engr.)

MEMBERSHIPS Fellow ('85), APS ; Fellow ('87), ASME; Associate Fellow ('76), AIAA

PROFESSIONAL EXPERIENCE 1989 - Cullen Distinguished Professor, U. of Houston (UH)
 1985 - 89 Distinguished University Professor, UH
 1976 - Professor, Mech. Engr. Dept., UH
 1973 - 76 Assoc. Prof., Mech. Engr. Dept., UH
 1971 - 73 Asst. Prof., Mech. Engr. Dept., UH
 1969 - 71 Visiting Asst. Prof., Dept. of Mechanics, The Johns Hopkins U.

Director, Institute for Fluid Dynamics and Turbulence, UH (1991 -)

TECHNICAL EXPERTISE Turbulence, vortex dynamics, aerodynamics, combustion, hydrodynamic stability, chaos, aeroacoustics, measurement techniques

CONSULTING NASA-Langley, NASA-Ames, Lockheed-Georgia, Southwestern Labs, Stauffer Chem. Co, NL Industries, Flow Industries, Spectron Labs, Inst. of Comp. Fluid Dyn.(Tokyo)

EDITORSHIPS Associate Editor, *The Physics of Fluids*, American Institute of Physics (1981-84)
 Assistant Editor, *Turbulence in Liquids*, 1975 - 1983 Biennial Volumes, Science Press
 Editorial Advisory Board, *Experimental Thermal and Fluid Science*, Elsevier Press (1988 -)

BOOK *Nonlinear Dynamics of Structures*, 1991 (eds. Sagdeev, Frisch, Hussain, Moiseev & Erokhin), World Scientific

SOME PANELS/ SCIENTIFIC COMMITTEES Advisory Committee, NASA-Stanford Center for Turbulence Research (1988 - 91)
 Advisory Board, Institute of Computational Fluid Dynamics (Tokyo)
 Advisory Board, 3rd(1981) through 8th(1991) *Symposia on Turbulent Shear Flows*
 Organizing Committee, *Biennial Symposia of Turbulence*, U. of Missouri-Rolla, (1975 -)
 Organizing and Scientific Committee, *Beer-Sheva International Seminar on MHD and Turbulence*, Israel,(1985 -)
 Vice-Chairman, *Int. Symp. on Generation of Large Structures in Continuous Media*, Perm - Moscow, June 11-20 (1990)
 Technical Committee on Turbulence, ASCE (1987 - 91)
 Asian Fluid Mechanics Committee (1979 -)
 Scientific Committee, *Int. Symp. on Transport Phenomena* U. of Tokyo (1987)
 Scientific Committee, *IUTAM Symposium on Topological Fluid Mech.* Cambridge U.(1989)
 Fluid Dynamics Prize Committee, APS (1991 -)
 Scientific Committee, *IUTAM Symposium on Eddy Structure Identification in Free Turbulent Shear Flows*. Poitiers, France (1992)

RESEARCH AWARDS *Eckhart Prize* (for outstanding Ph.D. Thesis), Stanford University, (awarded in 1971)
Senior Research Excellence Award, Cullen College of Engineering, UH, 1979
Exchange Scholar: 1980 (India), 1983 (China)
1984 Freeman Scholar, (biennial award of ASME)
Senior Research Excellence Award, UH, (first recipient) 1985

RESEARCH ACTIVITY SUMMARY 129 Archival papers
 69 Conference proceedings papers
 115 Oral presentations at major conferences (exclusive of invited lectures)
 55 Invited lectures at international meetings (including keynote lectures)
 Invited seminars (over 150 in USA and abroad)
 59 Competitive research grants

STEVEN A. ORSZAG

Steven A. Orszag is the Hamrick Professor of Engineering and Director and Professor of Applied and Computational Mathematics at Princeton University. He studied at M.I.T. and Cambridge University prior to receiving his Ph.D. in Astrophysics from Princeton in 1966. After a year at the Institute for Advanced Study, he returned to M.I.T. where he was Professor of Applied Mathematics until assuming his present position in 1984. His research interests include numerical analysis, applied mathematics, and fluid dynamics. His major contributions include the development of spectral numerical methods, the theoretical analysis of the mechanism of transition in shear flows, the first numerical simulations of three-dimensional turbulent flows, and the development of dynamic renormalization group methods for turbulence. His recent awards include the 1986 AIAA Fluids and Plasmadynamics Award, a Guggenheim Fellowship, and the 1991 Otto Laporte Award of the American Physical Society. Prof. Orszag is Editor-in-Chief of the Journal of Scientific Computing, Amer. Inst. of Physics Series in Computational Physics, and Springer Series in Computational Physics. He has written over 250 papers and 9 books. He is co-author with Carl M. Bender of the widely used Advanced Mathematical Methods for Scientists and Engineers and the forthcoming Partial Differential Equations for Scientists and Engineers.

DANIEL M. NOSENCHUCK

[REDACTED]
[REDACTED]
(office): (609)258-5136

PII Redacted

EDUCATION

- Ph.D. California Institute of Technology, Pasadena, California
Aeronautics, Thesis Advisor: H.W. Liepmann / June 1982
- M.S. California Institute of Technology, Aeronautics / June 1977
- B.S. Syracuse University, Syracuse New York
Aeronautical and Mechanical Engineering, cum laude / May 1976

EXPERIENCE

- 7/88 - Present Associate Professor of Mechanical and Aerospace Engineering
- 8/83 - 6/88 Assistant Professor
Princeton University, Princeton New Jersey

Teach graduate and undergraduate courses in fluid mechanics.

Current research areas:

- 1) development and application of the Navier-Stokes Computer
- 2) experimental and numerical fluid mechanics:
control of complex turbulent and vortical flows

HONORS

- Presidential Young Investigator Award (NSF), 1984-1989
- GTE Emerging Scholar, 1987
- Rheinstine Award, School of Engineering, Princeton University, 1986
- IBM Faculty Development Award 1984 - 1985
- EMMY Award from the Academy of Television Arts and Sciences for
Outstanding Individual Achievement - Special Visual Effects:
'*The Day After*,' 1984
- The William F. Ballhaus Prize,
for an 'Outstanding Doctoral Dissertation in Aeronautics,'
California Institute of Technology, 1982
- Graduate Fellowships, California Institute of Technology, 1976

MISCELLANEOUS

Patents:

- U.S. Patent No. 4811214 (March 1989): 'Dynamic Reconfiguration System for Pipelined Computers', Numerous foreign patents also awarded.
- U.S. Patent Pending: 'A Parameterized Optimizing Compiler'

Reviewer for:

- AIAA Journal
- Journal of Fluid Mechanics
- Physics of Fluids
- Review of Scientific Instruments

Department of Defense Activities:

- Member of Defense Science Board Ballistic Missile Defense Task Force
- Member of Defense Science Study Group

Consultant to:

- Defense Science Board, Washington DC
- DSV Partners, Princeton, NJ
- Institute for Defense Analysis, Alexandria VA
- Northwest Research Associates Inc., Bellevue WA
- Praxis Film Works, North Hollywood, CA
- Union Camp Corporation, Lawrenceville, NJ

Transferred Navier-Stokes Computer technology from Princeton University to Concurrent Computer Corporation, Tinton Falls, NJ, in 1987, and Supercomputer Solutions Inc, San Diego, CA., in 1989.

DANIEL M. NOSENCHUCK

Associate Professor

Daniel M. Nosenchuck's research interests include experimental and computational fluid mechanics, dynamic flow visualization, and advanced supercomputer architectures. His major contributions include experimental active laminar-flow control, the first successful demonstration of active turbulence control, and the development of a parallel-processing supercomputer. He was a charter-year recipient of the five-year NSF Presidential young Investigator Award (1984-89). He also received the IBM Faculty Development Award (1984-85) and the Princeton University School of Engineering Rhinestein Award (1986) for work related to the implementation of unique flow fields, and the development of new flow visualization techniques. He received the National EMMY Award in 1984 for Outstanding Individual Achievement in Special Visual Effects. He is active in industrial consulting and also consults directly with the Department of Defense, and is a member of DoD Defense Science Board Task Forces.

The underlying theme of his work revolves around the control of complex fluid flows. To achieve this, he is currently engaged in several areas of research. These include the study and experimental active control of turbulent boundary-layers in a low-speed water channel, wake-vortex prediction and control, the development of a new three-dimensional dynamic flow-visualization technique, and the design and construction of a very-high-speed computer for use in complex flow simulations and control applications.

Experimental Fluid Mechanics

The goal of this research is to reduce skin-friction drag by modifying turbulent boundary layers. A new technique using a wall-normal electromagnetic body force to directly suppress near-wall turbulent instabilities is in the early stages of development. Preliminary experimental results indicate the possibility of dramatic reductions in turbulence and wall-shear with little power expenditure. Other experiments involve arrays of thin-film, sensors and actuators coupled to high-speed feedback-control electronics. With appropriate special-purpose electronics, a significant attenuation of boundary-layer instabilities has been realized. A second major area of investigation is the mitigation of the wake-vortex hazard produced behind large aircraft, and the alleviation of trailing vortices behind submarines. This is being investigated using a new approach to induce instabilities in the vortex sheet produced by lifting surfaces. Through the development and application of an optimizing numerical design and flow simulation procedure, small modifications to the lifting surface geometry were predicted to modify substantially the trailing vortex. Preliminary experiments were used to validate the predictions.

To understand these complex, nonsteady boundary-layer and vortex flows, a new diagnostic technique was developed within the lab. A laser-sheet is rapidly scanned through flow-fields into which a laser-fluorescing dye has been added, and a series of two-dimensional images are obtained. A single scan is comprised of many closely-spaced sheets. From this space-filling data set, a three-dimensional flow visualization image, representative of one instant in the flow, is obtained. Repeated scanning is used to create a complete three-dimensional nonsteady qualitative record of the flow. He is currently extending the technique to encompass quantitative methods, and investigating its use as a real-time input sensor for active control experiments.

Navier-Stokes Computer

Problems in fluid mechanics involving complex flow simulations require far more speed and capacity than that provided by current and proposed conventional and parallel supercomputers. To address this concern, the Navier-Stokes Computer (NSC) was developed. The NSC is a fully general-purpose parallel-processing machine, comprised of individual Nodes, each comparable in performance to current supercomputers. The projected speed and capacity of a 128-Node NSC is many orders-of-magnitude greater than that of existing supercomputers. New architectural features have provided the capability to efficiently address a far greater range of problems than possible on conventional machines. The first large-scale applications of the NSC involved the simulation of complex flows at moderate Reynolds-numbers, including nonsteady flows with separation over a large domain. A fast optimizing NSC FORTRAN compiler, which uses a new 'approximate simulation' technique coupled is in development.

Selected Publications

"The Direct Control of Wall Shear Stress in a Turbulent Boundary Layer," (with G.L. Brown), submitted to Phys. Rev. Lett., 1992.

"Parameterized Memory/Processor Optimizing FORTRAN Compiler for Parallel Computers," To be published in Proceedings of 1992 Scalable High Performance Computing Conference, IEEE Computer Society Press.

"Control of Wingtip Vortices," (with W.S. Flannery and G.L. Brown) Proceedings of FAA Wake Vortex Symposium, Washington, DC, 29-31 October 1991.

"The Navier-Stokes Computer," Special-Purpose Computers, (with W.S. Flannery and E. Hayder) B. Alder, ed., pp 97 - 134, 1988.

"Active Control of Sublayer Disturbances Using an Array of Heating Elements," (with M. K. Lynch and J. P. Stratton) Proc. 2nd ASME/JSME Thermal Engineering Joint Conf., 1987.

"Three-Dimensional Flow Visualization Using Laser-Sheet Scanning," (with M. K. Lynch). Proceedings of the AGARD Conference on Aerodynamic and Related Hydrodynamic Studies Using Water Facilities, AGARD Conference Preprint No. 413, pp 18-1 - 13, 1986.

"Active Control of Laminar-Turbulent Transition," (with H.W. Liepmann). J. Fluid Mech. Vol 118, pp 201-204, 1982.

GARRY L. BROWN
Professor and Chairman

Garry L. Brown was appointed Chairman of the Department of Mechanical & Aerospace Engineering at Princeton University in July, 1990. He arrived at Princeton after 9 years as Director of the Aeronautical Research Laboratory, Department of Defense, Melbourne, Australia. Prior to that he was a Professor of Aeronautics at the Graduate Aeronautical Laboratories at California Institute of Technology and a senior reader and lecturer in Mechanical Engineering at the University of Adelaide, Australia. Prof. Brown has published widely in the field of turbulence and more recently on vortex breakdown. His work with Prof. Roshko which reported the discovery of coherent structure in turbulent mixing layers has been recognized by the Journal of Fluid Mechanics as a "classic paper." His work with Wallace (at Adelaide University) and subsequently with Mungal (at CalTech) developed a new way of conducting combustion experiments at high Reynolds numbers in highly reactive gases. His collaboration with Liepmann and Nosenchuck on the control of boundary layer transition has been recognized as an important result in the development of turbulence control. Recent work with Lopez (at the Aeronautical Research Laboratories) on the classic problem of axisymmetric vortex breakdown has led to a new necessary criterion for vortex breakdown based on the development of negative azimuthal vorticity. Prof. Brown is continuing his work on vortex dynamics, turbulence and compressible gas dynamics in collaboration with other members of the department.

Sample Publications:

1. G.L. Brown and A. Roshko, "On Density Effects and Large Structure in Turbulent Mixing Layers," *J. Fluid Mech.* **64**, pp. 775-816 (1974).
2. P.E. Dimotakis and G.L. Brown, "The Mixing Layer at High Reynolds Number: Large Structure Dynamics and Entrainment," *J. Fluid Mech.* **78**, pp. 535-560 (1976).
3. G.L. Brown and Andrew S.W. Thomas, "Large Structure in a Turbulent Boundary Layer," *Phys. Fluids*, **20**, No. 10, Pt. II, pp. 243-252 (1977).
4. H.W. Liepmann, G.L. Brown, and D.M. Nosenchuck, "Control of Laminar-Instability Waves Using a New Technique," *J. Fluid Mech.* **118**, pp. 187-200 (1982).
5. G.L. Brown and J.M. Lopez, "Axisymmetric vortex breakdown, Part 2. Physical mechanisms," *J. Fluid Mech.* (1990), vol. **221**, pp. 553-576.

Anatol Roshko
Aeronautics Department 105-50
California Institute of Technology
Pasadena, CA 91125
(818) 356-4484

Date and Place of Birth:

████████████████████

PII Redacted

Education

| | |
|-------------------------------------------------------|------|
| B.Sc. Engineering Physics, University of Alberta | 1945 |
| M.S. Aeronautics, California Institute of Technology | 1947 |
| Ph.D. Aeronautics, California Institute of Technology | 1952 |

Academic Experience

| | |
|--------------------------------------------------------------|---------|
| Instructor (Mathematics) University of Alberta | 1945-46 |
| Lecturer (Engineering) University of Alberta | 1949-50 |
| Research Fellow (Aeronautics) Caltech | 1952-55 |
| Assistant Professor (Aeronautics) Caltech | 1955-58 |
| Associate Professor (Aeronautics) Caltech | 1958-62 |
| Professor (Aeronautics) Caltech | 1962- |
| Theodore von Kármán Professor of Aeronautics | 1985- |
| Acting Director, Graduate Aeronautical Laboratories, Caltech | 1985-87 |

Consultant

McDonnell-Douglas Corporation
Rockwell International
General Motors Corporation

Professional Societies

U.S. National Academy of Engineering
American Academy of Arts and Sciences (Fellow)
Canadian Aeronautics and Space Institute (Fellow)
International Academy of Astronautics (Corresponding Member)
American Physical Society (Fellow)
American Institute of Aeronautics and Astronautics (Fellow)
Artic Institute of North America
American Association of University Professors
Sigma Xi
Wind Engineering Research, Inc. (Founding Director)

Fields of Interest

- (1) Turbulent Shear Flow
- (2) Separated Flow
- (3) Transonic and Supersonic Aerodynamics
- (4) Industrial Aerodynamics
- (5) Effect of Wind and Ocean Currents on Structures

Committees, etc.

| | |
|-----------------------------------------------------------------------------|---------|
| Associate Editor, Journal of Fluids and Structures | 1986– |
| Technical Committee on Turbulence Engineering Mechanics Division of ASCE | 1987– |
| Advisory Board Stanford/Ames Center for Turbulence Research | |
| National Research Council Aeronautics and Space Engineering Board | 1988– |
| Associate Editor, Physics of Fluids | 1971–73 |
| Scientific Liaison Officer, Office of Naval Research, London | 1961–62 |
| National Science Foundation Exchange Scientist to India | 1969 |
| U.S. Wind Engineering Research Council Board of Directors | 1978–85 |
| Member National Committee for Theoretical and Applied Mechanics | 1978–80 |
| Fluid Dynamics Panel of AGARD | 1984–89 |

Honors

| | |
|-------------------------------------------------------------------------------------------------|------|
| Dryden Research Lecture, AIAA | 1976 |
| Turnbull Lecture, Canadian Aeronautics and Space Institute | 1980 |
| Fluid Dynamics Prize, American Physical Society Division of Fluid Dynamics | 1987 |
| Award for Professional Achievement, University of Alberta | 1988 |
| Opening Lecturer, XVIIIth International Congress of Theoretical and Applied Mechanics, Haifa | 1992 |

DISTRIBUTION LIST

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