Figures to be held in the editorial files

(1)

Numerical analysis of gas-particle two-phase flows

(Numerical Results)

By Ryuji Ishii, Yoshikuni Umeda and Masatoshi Yuhi

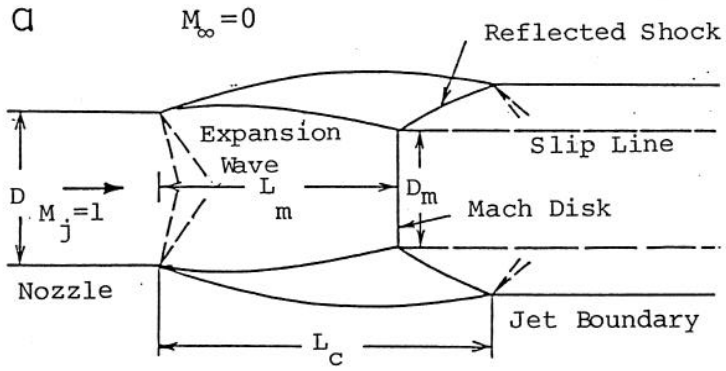
Department of Aeronautics, Kyoto University

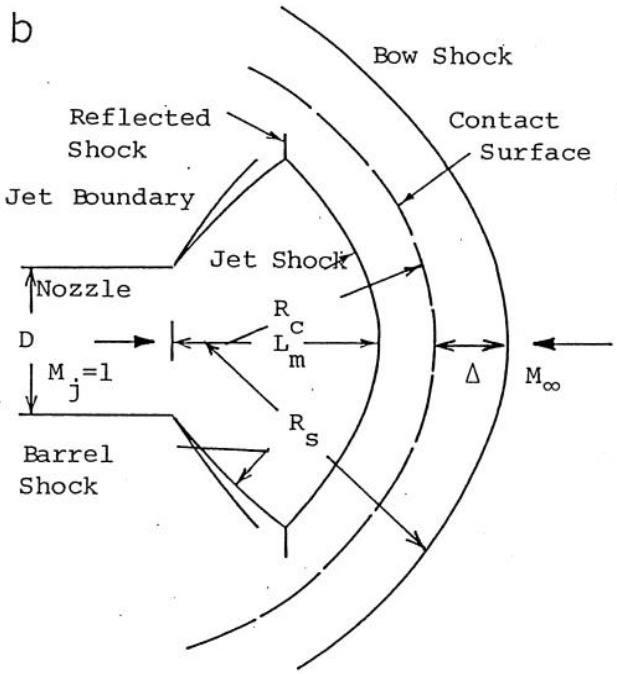
Yoshida Honmachi, Sakyo-ku, Kyoto 606, Japan

Table 1. Physical constants of gas and particles used in the numerical calculations.

Gas (Air)	Particles (Al_2O_3)
$\gamma = 1.4$	$\bar{\rho}_{mp} = 4.0 \times 10^3$ kg/m³
$\bar{C}_{pg} = 1005$ J/kg.K	$\bar{C}_{pp} = 1686$ J/kg.m
$\bar{\mu} = 1.79 \times 10^{-5}$ kg/m.s (for $\bar{T} = 288$ K)	
$\delta = 0.5$	
$P_r = 0.75$	

Calculated flowfields





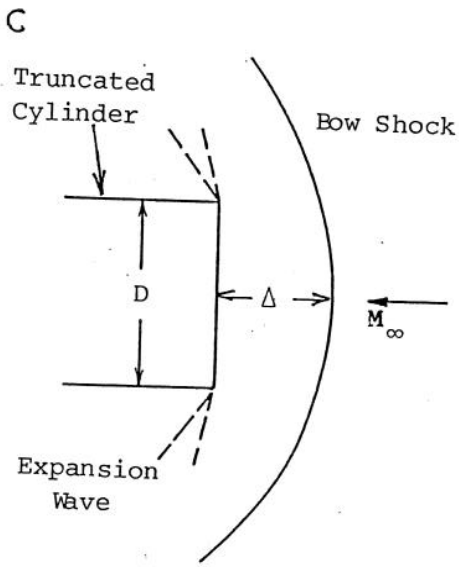


Figure captions

B-1) Time history of density profile along the jet axis of a dust-free jet for $\bar{p}_0/\bar{p}_\infty = 20$. The jet begins to blow into a stagnant ambient gas region at t = 0 (n = 0). The flow Mach number of the jet at the nozzle exit is $M_j = 1$; $\Delta x = \Delta y = 0.1$.

B-2) Time history of density profile along the axis of a dust-free opposing jet for $\bar{p}_0/\bar{p}_\infty = 20$. The jet begins to blow opposing to a uniform mainstream ($M_\infty = 2.0$) at t = 0 (n=0). The flow Mach number at the nozzle exit is $M_j = 1.0$; $\Delta x = \Delta y = 0.1$.

B-3) Time history of density profile along the body axis. A uniform supersonic flow ($M_\infty = 2.0$) impinges on a truncated cylinder at time t = 0 (n = 0); $\Delta x = \Delta y = 0.02$.

B-4) Time history of density profile along the jet axis of a dusty jet; $\bar{L} = 5$ cm, $\bar{p}_0 = 5$ atm, $\bar{p}_0/\bar{p}_\infty = 20$, $\bar{T}_0 = \bar{T}_\infty = 290$ K, $M_j = 1.0$, $M_\infty = 0$, $\nu_j = 0.3$, $\bar{r}_p = 1.0\ \mu$m, $\Delta x = \Delta y = 0.1$, K = 50, F=0.8. The particles are injected into the dust-free jet at the nozzle exit after n = = 6000.

B-5) Time history of density profile along the jet axis of a dusty opposing jet; $\bar{L} = 5$cm, $\bar{p}_0 = 5$ atm, $\bar{p}_0/\bar{p}_\infty = 20$, $\bar{T}_0 = \bar{T}_\infty = 290$ K, $M_j = 1$, $M_\infty = 2.0$, $\nu_j = 0.3$, $\bar{r}_p = 1.0\ \mu$m, $\Delta x = \Delta y = 0.1$, K = 50, F = 0.8. The particles are injected into the dust-free jet at the nozzle exit after n = 9000.

B-6) Time history of density profile along the body axis of a dusty supersonic flow around a truncated cylinder; $\bar{L} = 5$cm, $\bar{p}_\infty = 0.5$ atm, $\bar{T}_\infty = 290$K, $M_\infty = 2$, $\nu_\infty = 0.3$, $\bar{r}_p = 2\mu$m, $\Delta x = \Delta y = 0.05$, K = 250, F = 0.8. The particles are injected into the dust-free flow at a plane perpendicular to the body axis ahead of the bow shock after n=4000.

B-7) Velocity field of the dust-free jet shown in figure B-1.

B-8) Velocity field of the dust-free opposing jet shown in figure B-2.

B-9) Flow field of the dust-free supersonic flow around a truncated cylinder shown in figure B-3. These are obtained with finer mesh than those shown in the text.

B-10) Particle trajectories in the jet shown in figure B-1.

B-11) Particle trajectories in the opposing jet shown in figure B-2.

B-12) Particle trajectories in the supersonic flow around a truncated cylinder shown in figure B-3.

B-13) Velocity and temperature distributions along the jet axis of the dusty jet shown in figure B-4.

B-14) Velocity and temperature distributions along the jet axis of dusty opposing jet shown in figure B-5.

B-15) Distributions of flow quantities in the dusty shock layer shown in figure B-6:

a) Density distributions along the body axis.

b) Pressure distributions along the body axis.

c) Temperature distributions along the body axis.

d) Velocity distributions along the body axis.

e) Density distributions along the body wall.

f) Pressure distributions along the body wall.

B-16) Constant density contours of particle phase in the dusty shock layer shown in figure B-6.

B-17) Spatial distributions of particle clouds in the whole computational region for the dusty supersonic flow around a truncated cylinder shown in figure B-6.

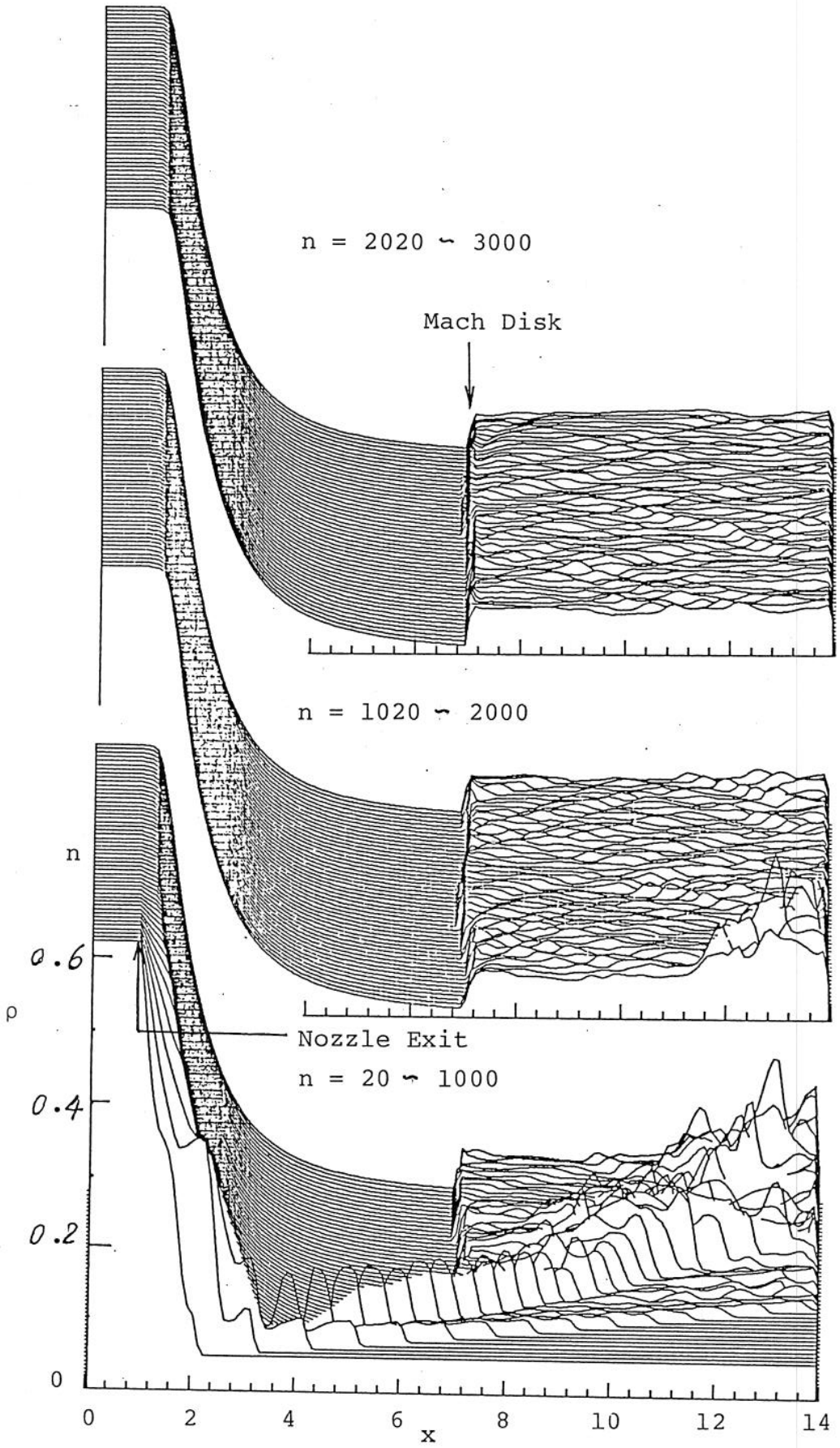

n = 2020 ~ 3000
Mach Disk
n = 1020 ~ 2000
n
0.6
ρ
Nozzle Exit
n = 20 ~ 1000
0.4
0.2
0
0
2
4
6
8
10
12
14
x

Fig. B-1 -1

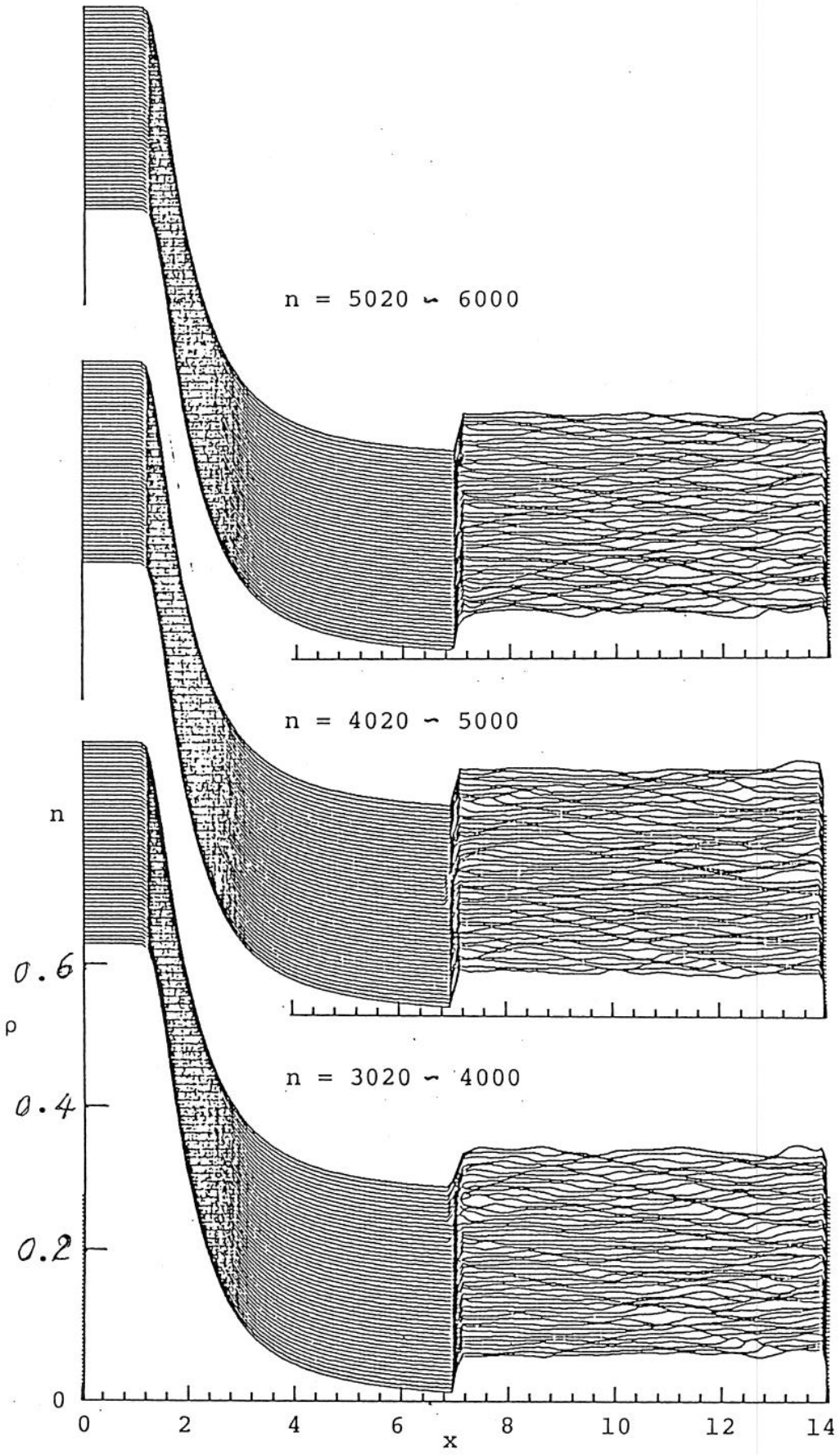


Fig. B-1 - 2

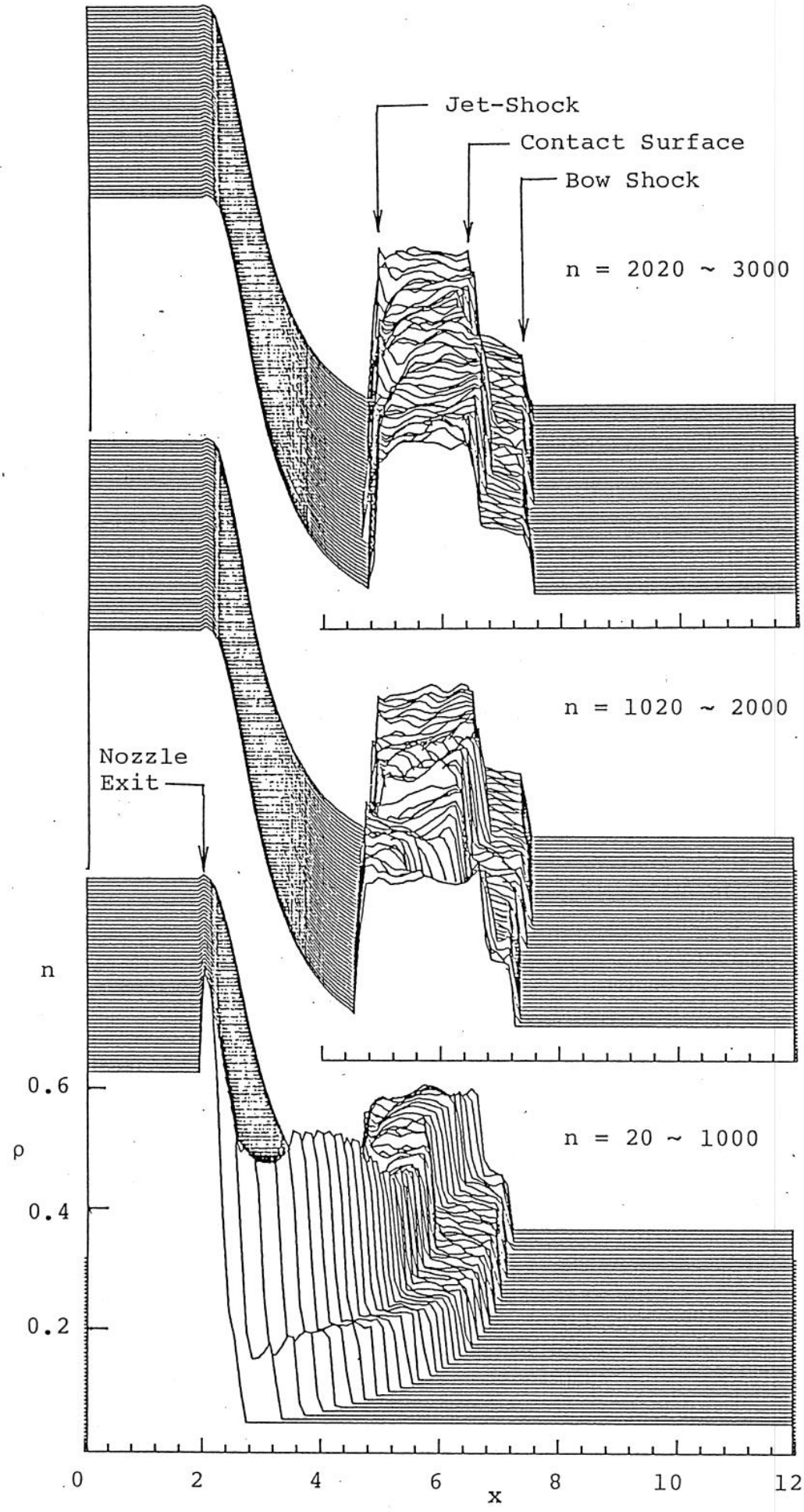

Jet-Shock
Contact Surface
Bow Shock
n = 2020 ~ 3000
n = 1020 ~ 2000
Nozzle
Exit
n
n = 20 ~ 1000
0.6
ρ
0.4
0.2
0
2
4
6
8
10
12
x

Fig. B-2 -1

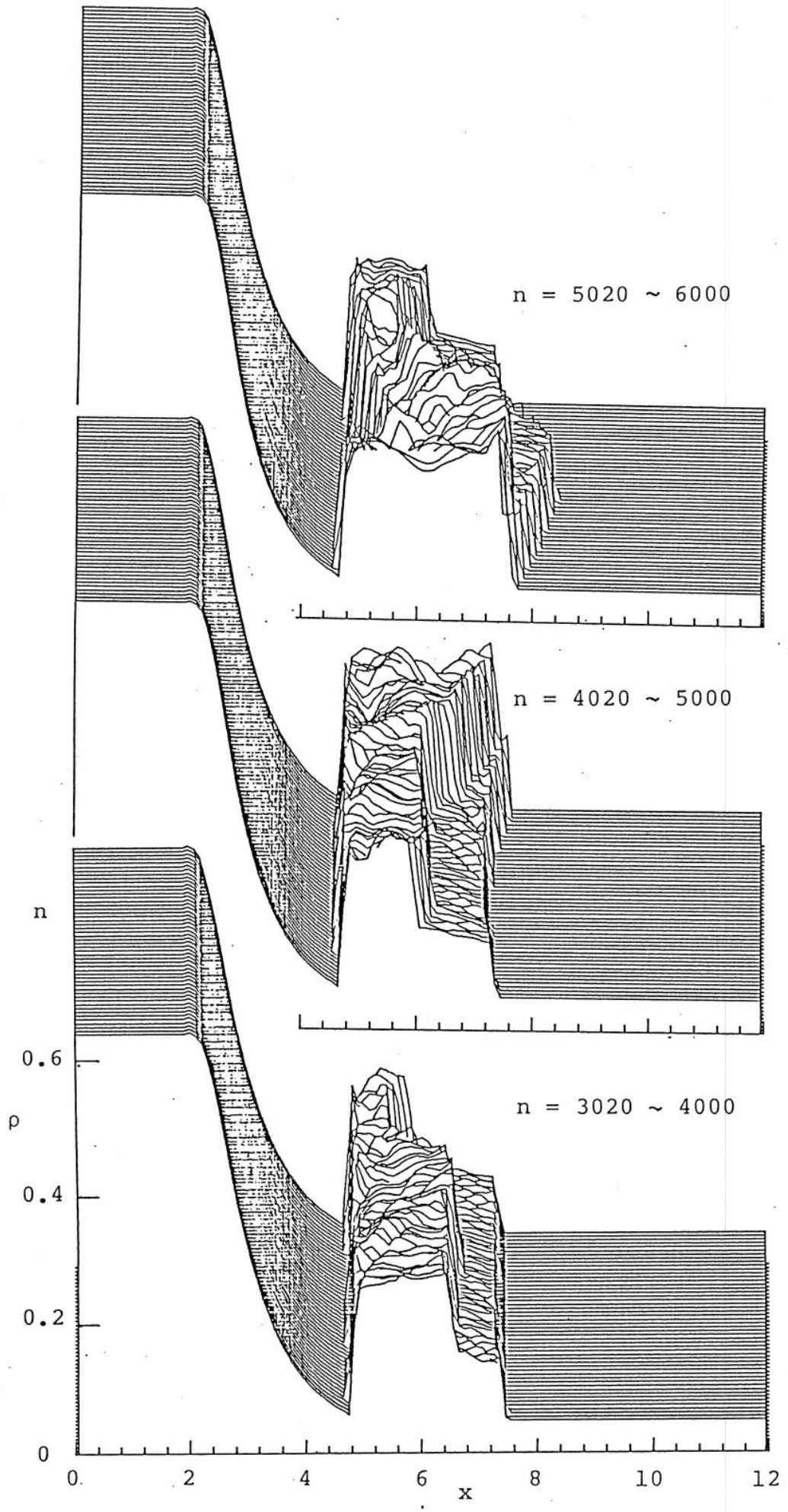


Fig. B-2 -2

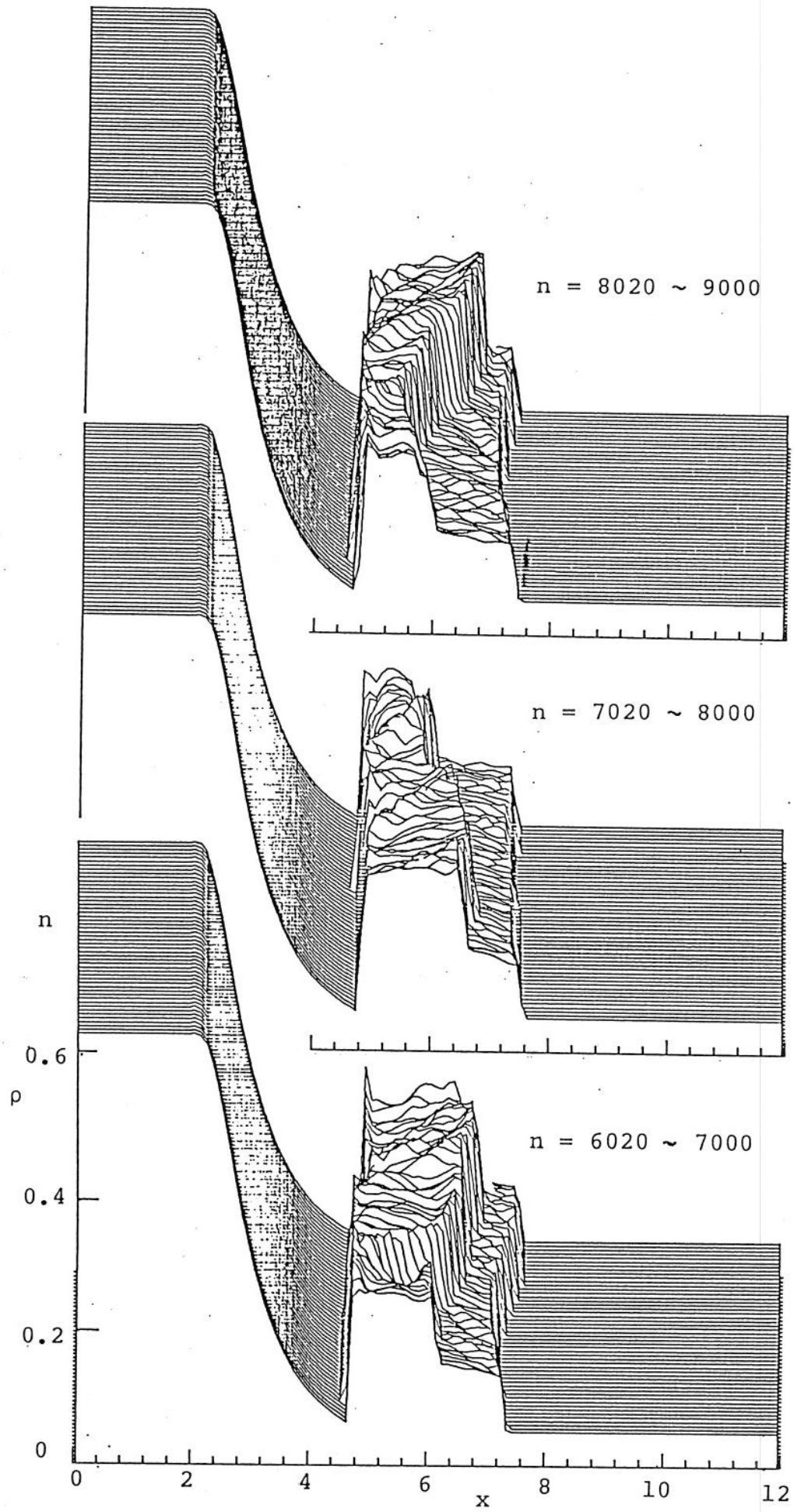


Fig. B-2 -3

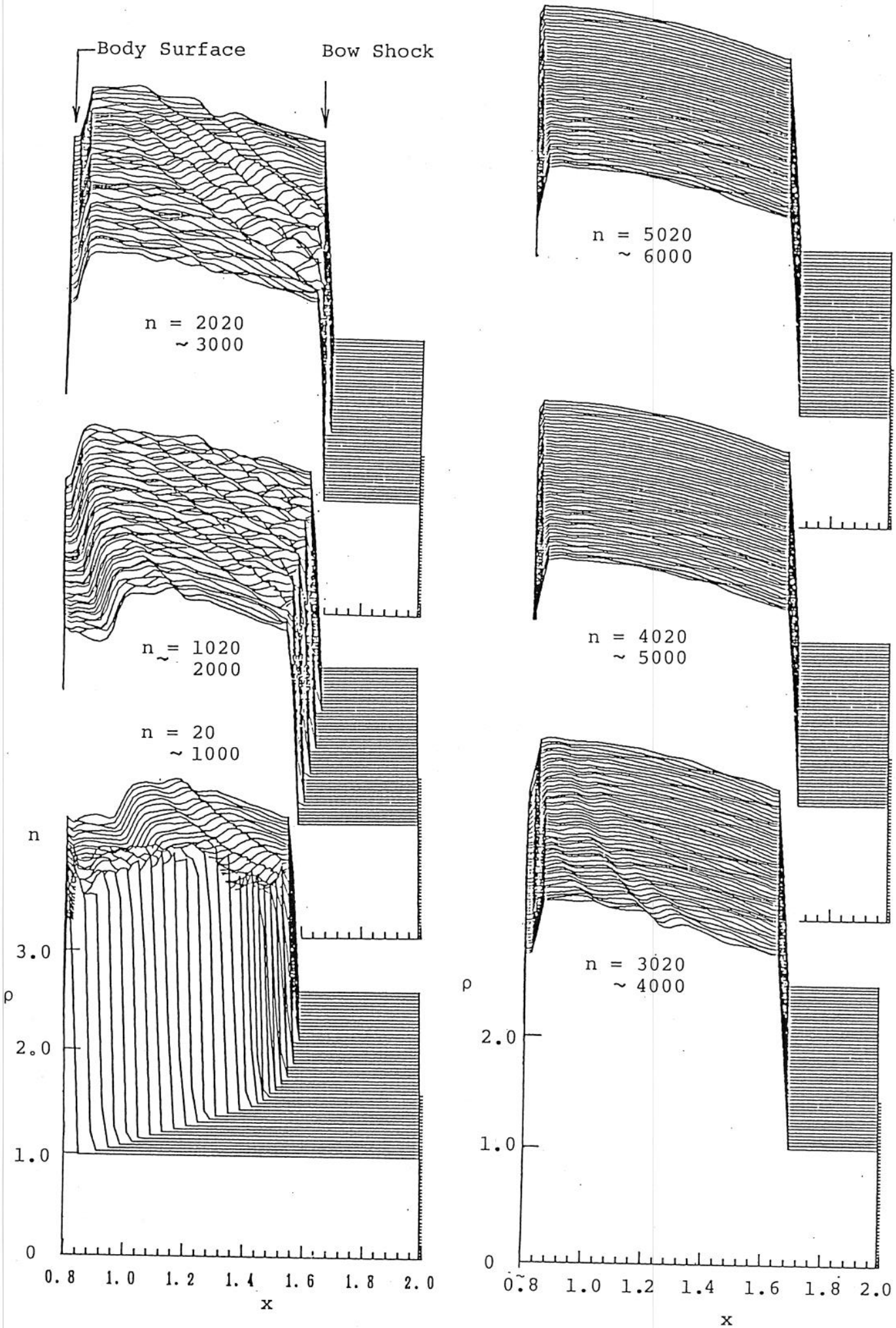

Body Surface
Bow Shock
n = 2020
~ 3000
n = 1020
~ 2000
n = 20
~ 1000
n = 5020
~ 6000
n = 4020
~ 5000
n = 3020
~ 4000
n
ρ
3.0
2.0
1.0
0
0.8
1.0
1.2
1.4
1.6
1.8
2.0
x

Fig. B-3

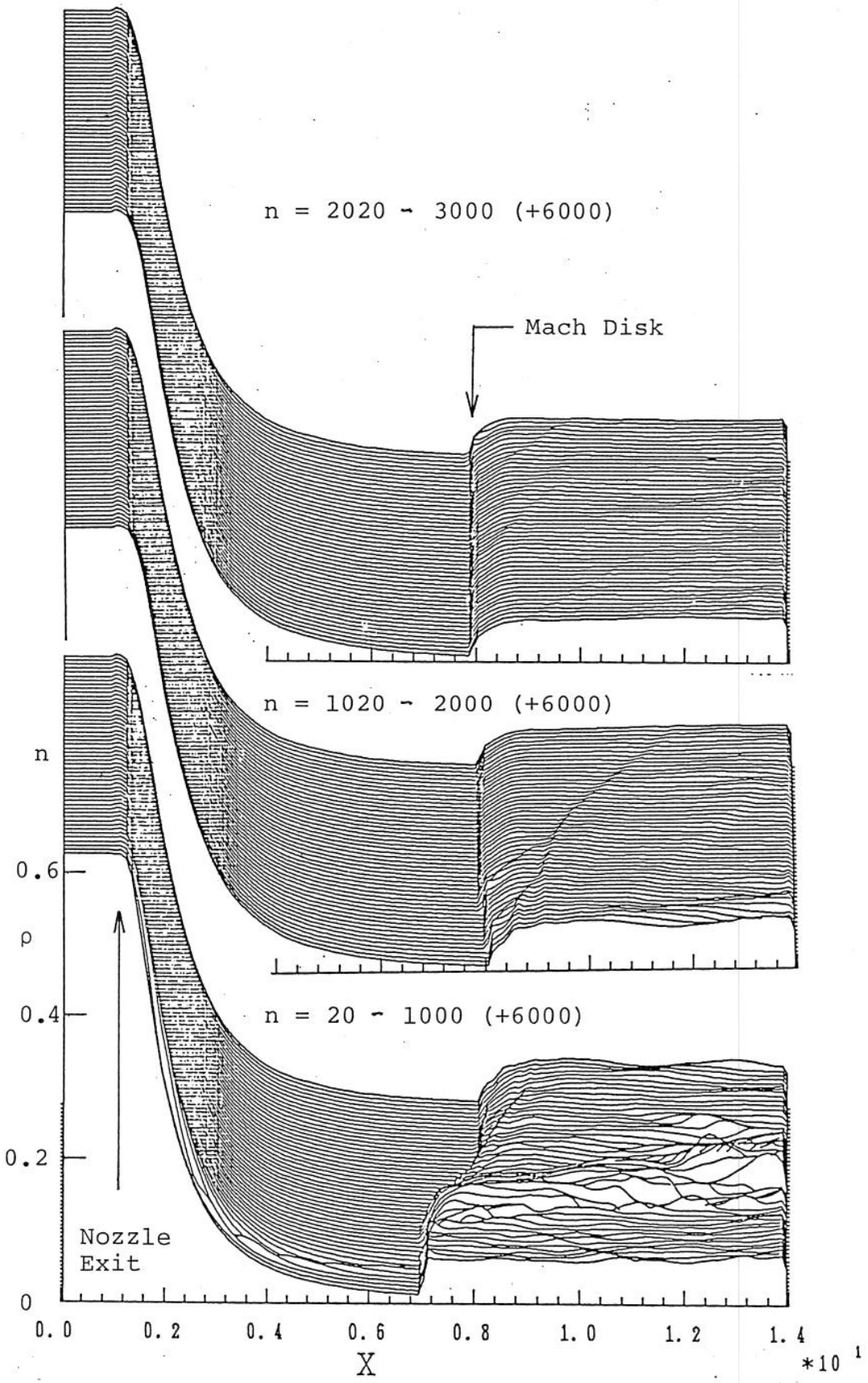

n = 2020 ~ 3000 (+6000)
Mach Disk
n = 1020 ~ 2000 (+6000)
n = 20 ~ 1000 (+6000)
n
0.6
ρ
0.4
0.2
0
Nozzle
Exit
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
X
*10 1

Fig. B-4 -1

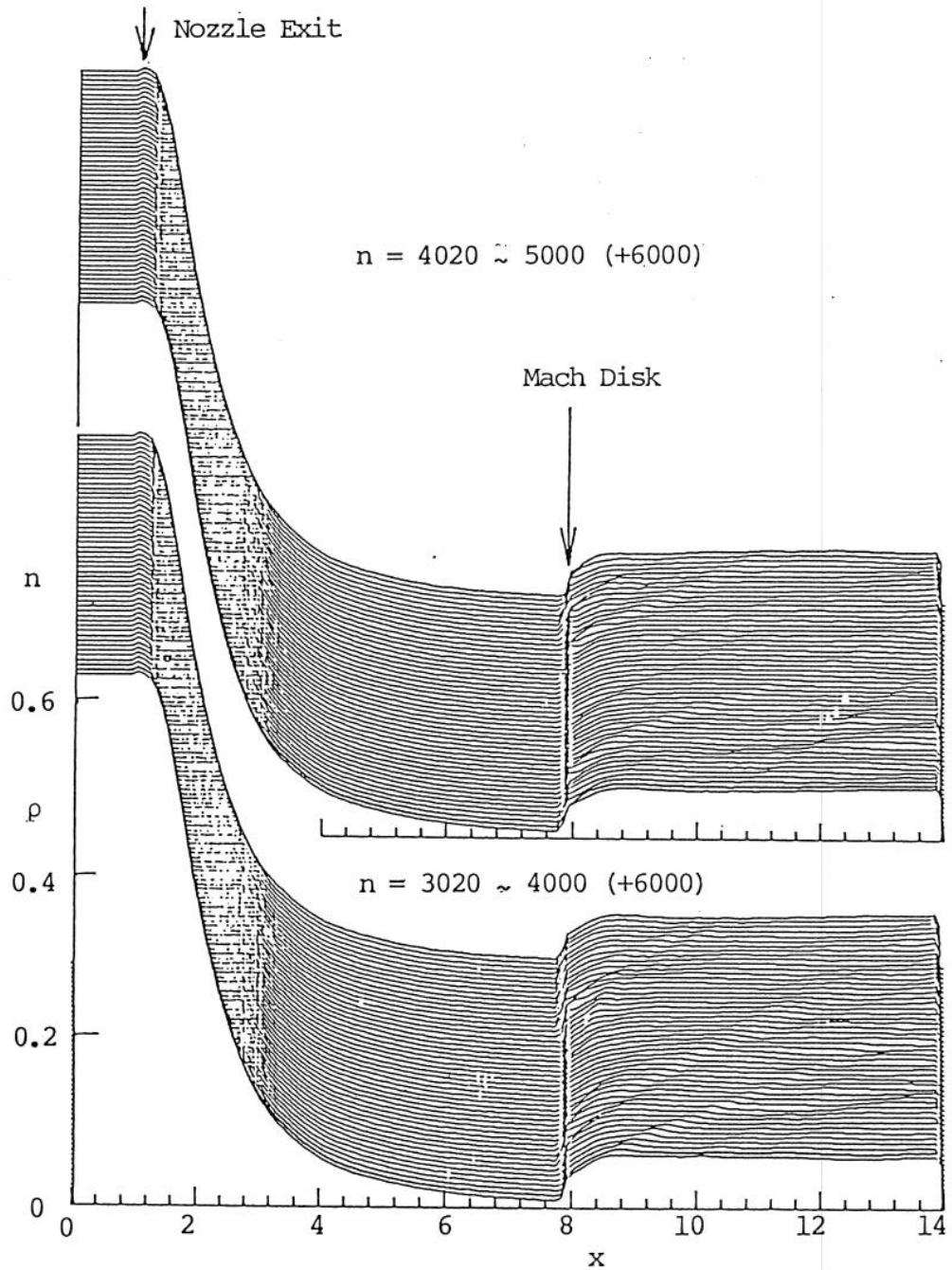

Nozzle Exit
n = 4020 ~ 5000 (+6000)
Mach Disk
n
0.6
ρ
0.4
n = 3020 ~ 4000 (+6000)
0.2
0
0
2
4
6
8
10
12
14
x

Fig. B-4 -2

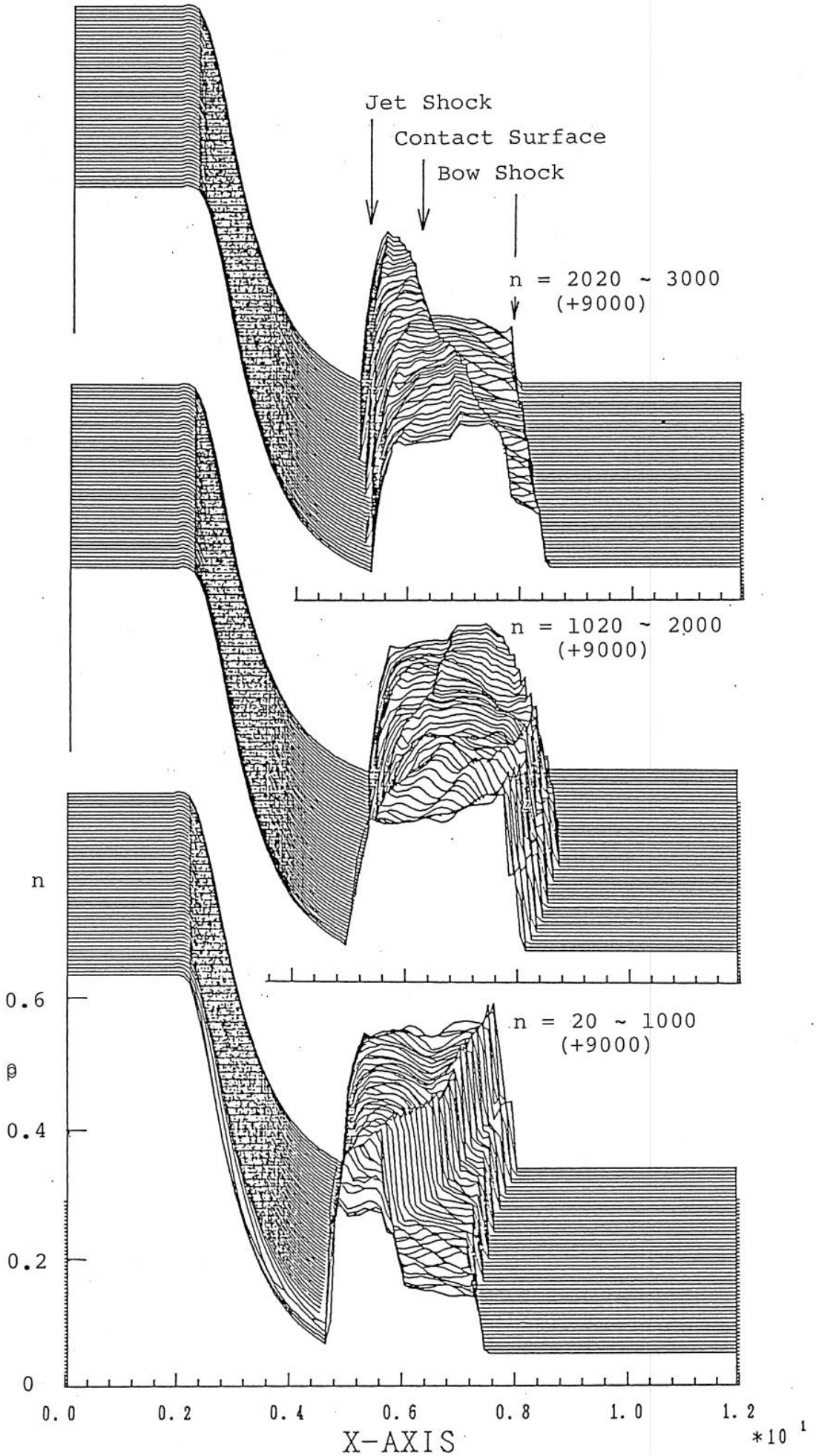

Jet Shock
Contact Surface
Bow Shock
n = 2020 ~ 3000
(+9000)
n = 1020 ~ 2000
(+9000)
n = 20 ~ 1000
(+9000)
n
β
0.6
0.4
0.2
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
X-AXIS
*10 1

Fig. B-5-1

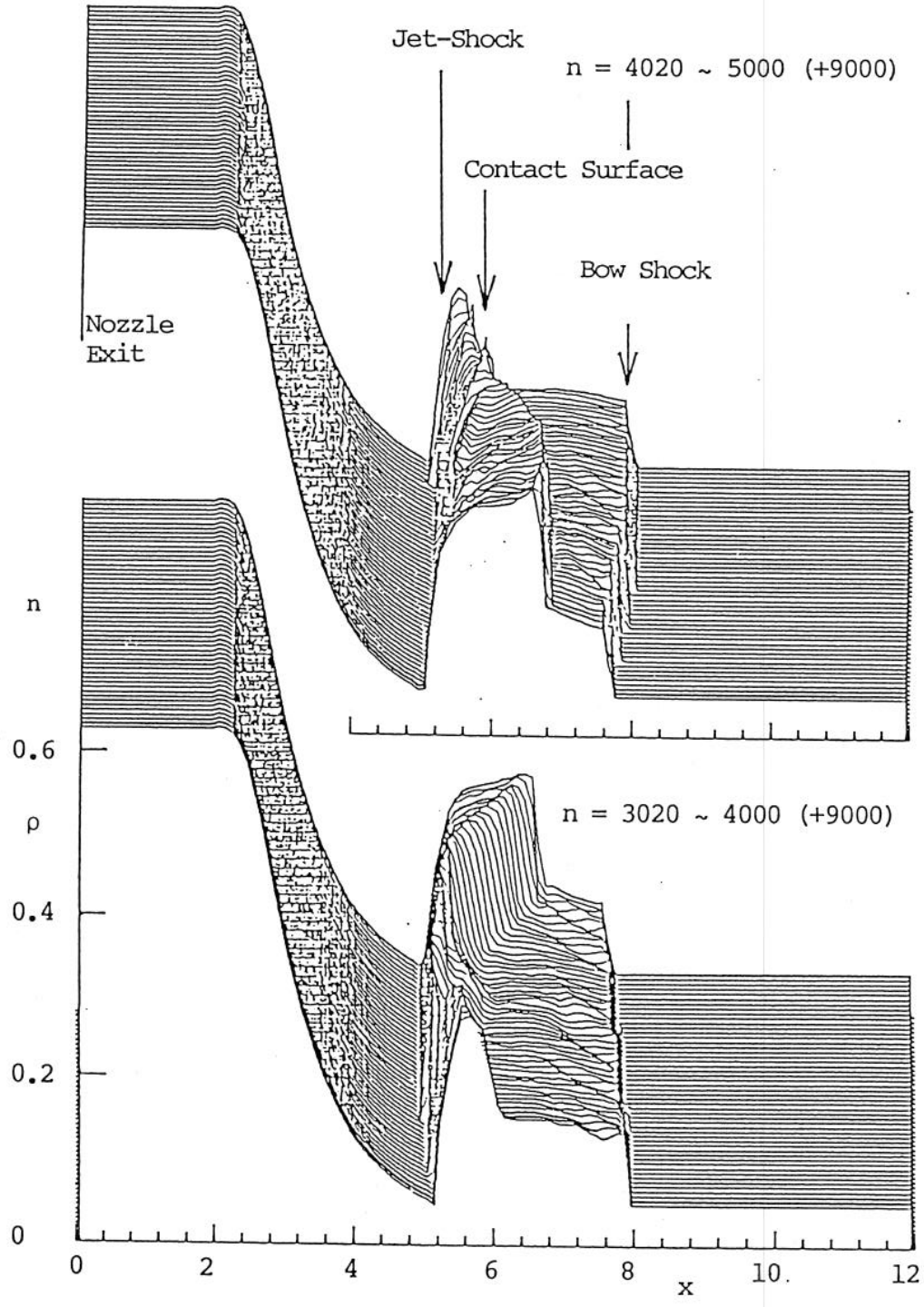

Jet-Shock
n = 4020 ~ 5000 (+9000)
Contact Surface
Bow Shock
Nozzle
Exit
n
0.6
ρ
0.4
0.2
0
n = 3020 ~ 4000 (+9000)
0
2
4
6
8
10
12
x

Fig. B-5 - 2

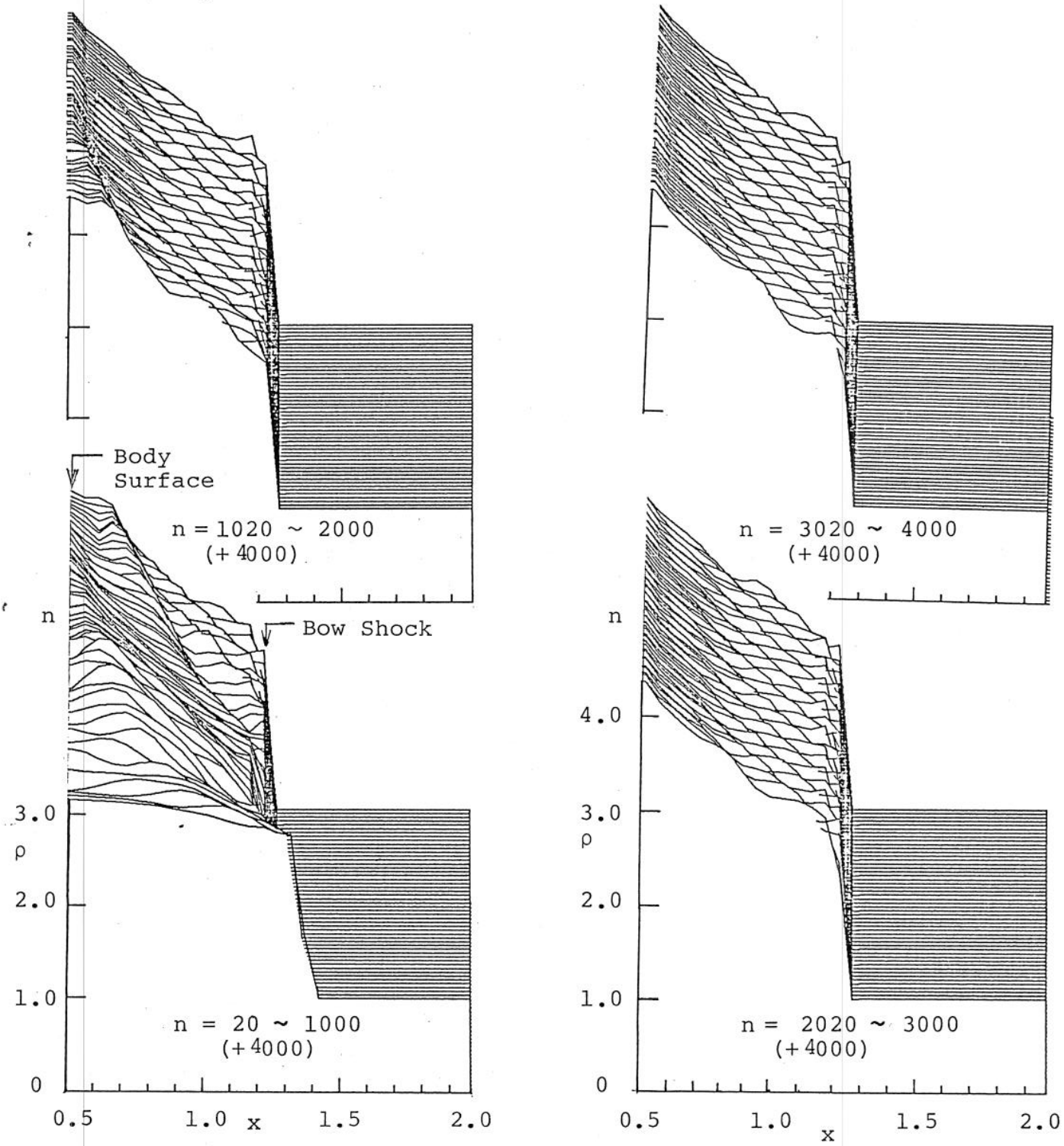

Body
Surface
n = 1020 ~ 2000
(+4000)
Bow Shock
n
n = 20 ~ 1000
(+4000)
3.0
ρ
2.0
1.0
0
0.5
1.0
x
1.5
2.0
n = 3020 ~ 4000
(+4000)
n
4.0
3.0
ρ
2.0
1.0
n = 2020 ~ 3000
(+4000)
0
0.5
1.0
x
1.5
2.0

Fig. B-6

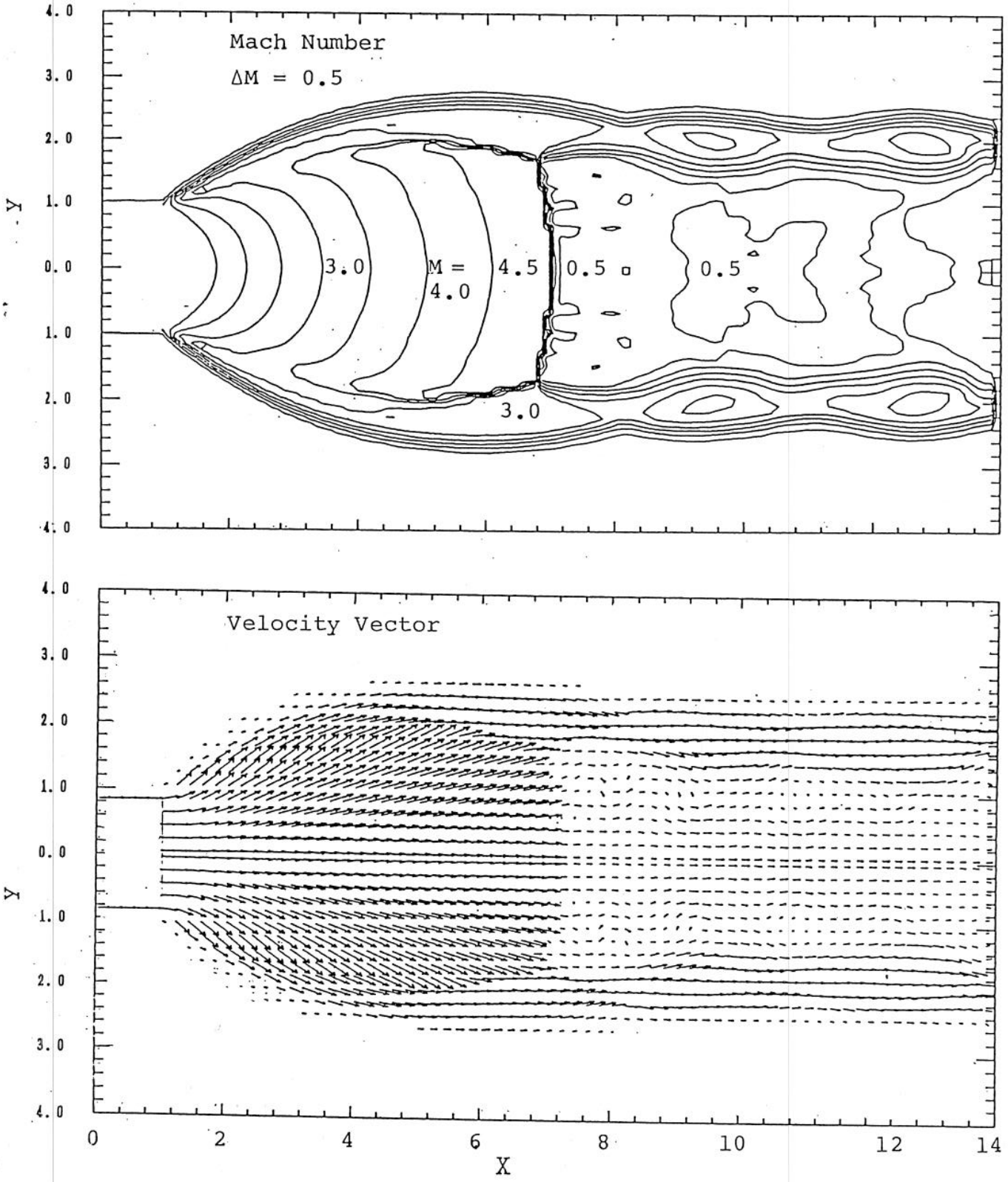
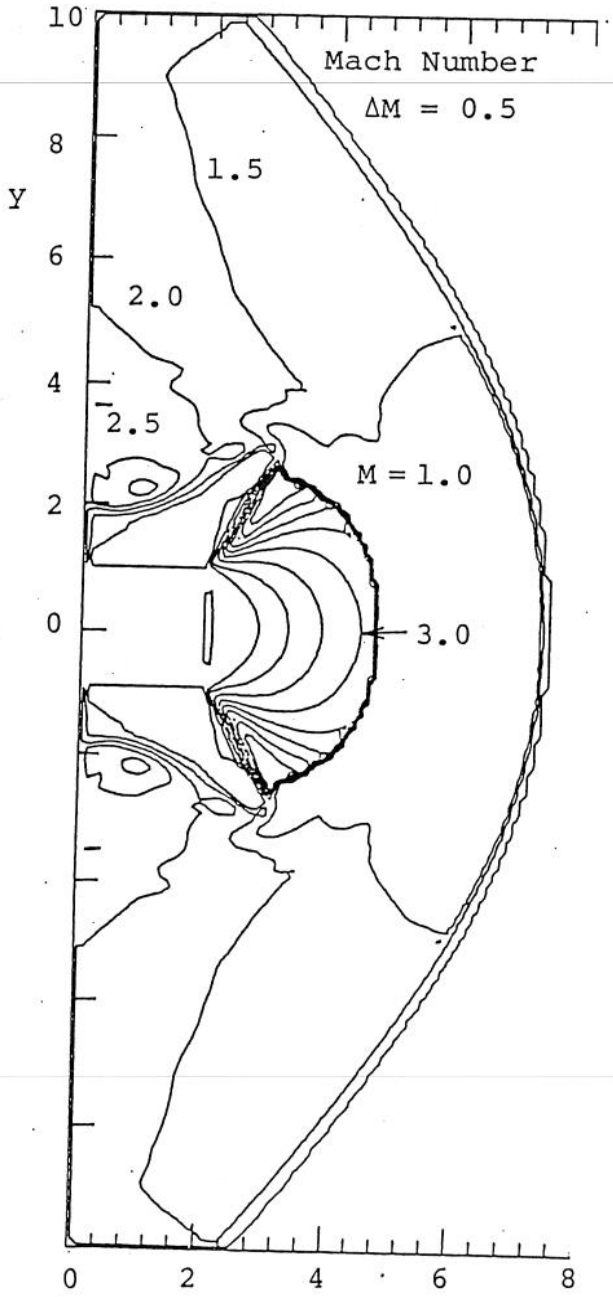

Mach Number
ΔM = 0.5
3.0
M = 4.0
4.5
0.5
0.5
3.0
Velocity Vector
Y
X
4.0
3.0
2.0
1.0
0.0
1.0
2.0
3.0
4.0
0
2
4
6
8
10
12
14

Fig. B-7


Mach Number
ΔM = 0.5
1.5
2.0
2.5
M = 1.0
3.0
Y
10
8
6
4
2
0
0
2
4
6
8

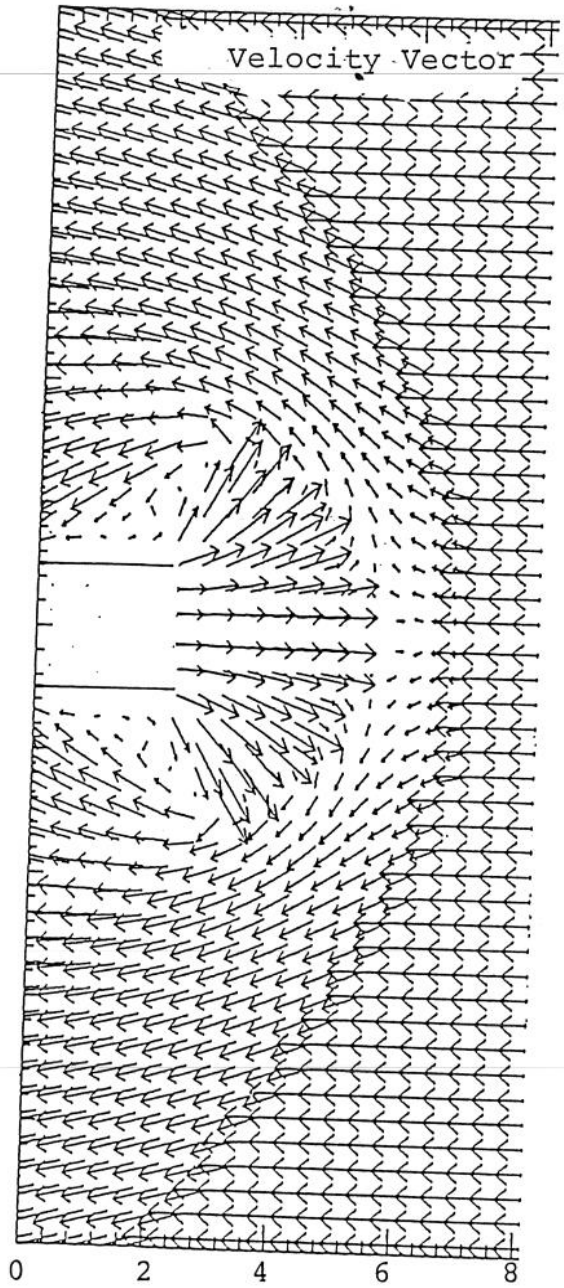

Velocity Vector
0
2
4
6
8

Fig. B-8

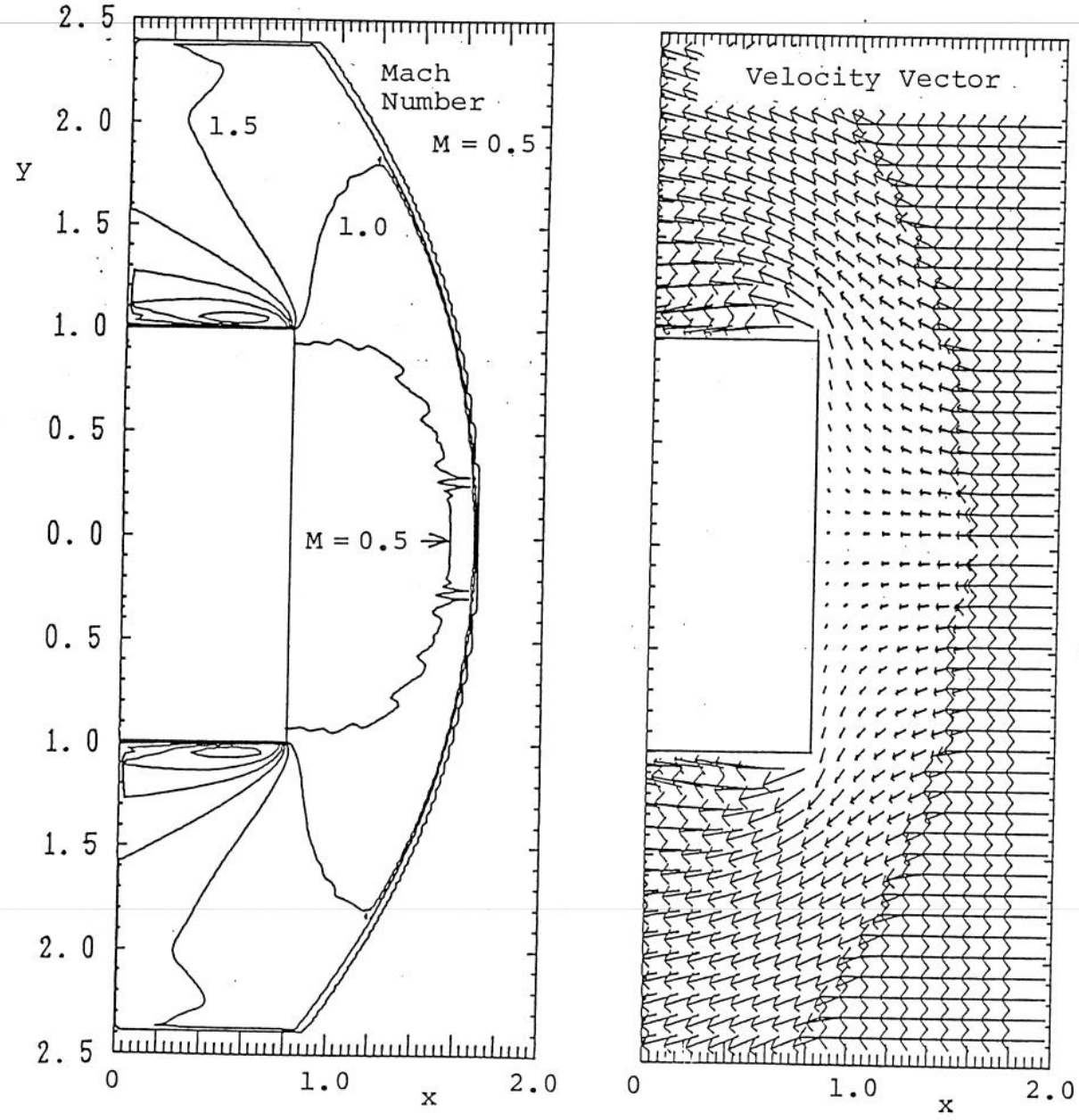

Mach
Number
1.5
1.0
M = 0.5
M = 0.5
Velocity Vector
y
x
x
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
2.5
0
1.0
2.0
0
1.0
2.0

Fig. 8-9-1

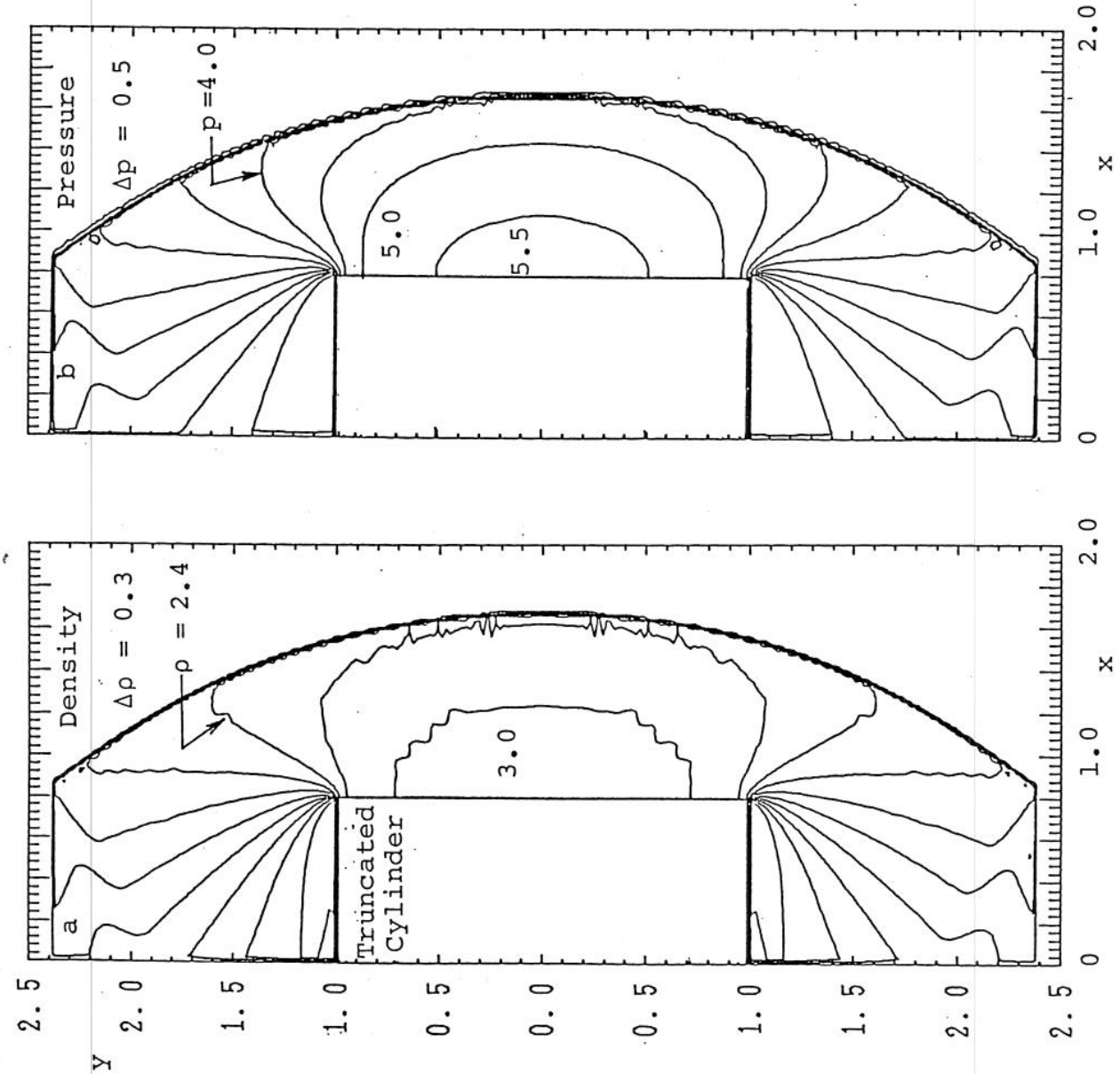

Pressure
Δp = 0.5
p=4.0
5.0
5.5
b
Density
Δρ = 0.3
ρ = 2.4
3.0
a
Truncated
Cylinder
x
y
0
1.0
2.0
2.5
1.5
0.5
0.0

Fig. B-9-2

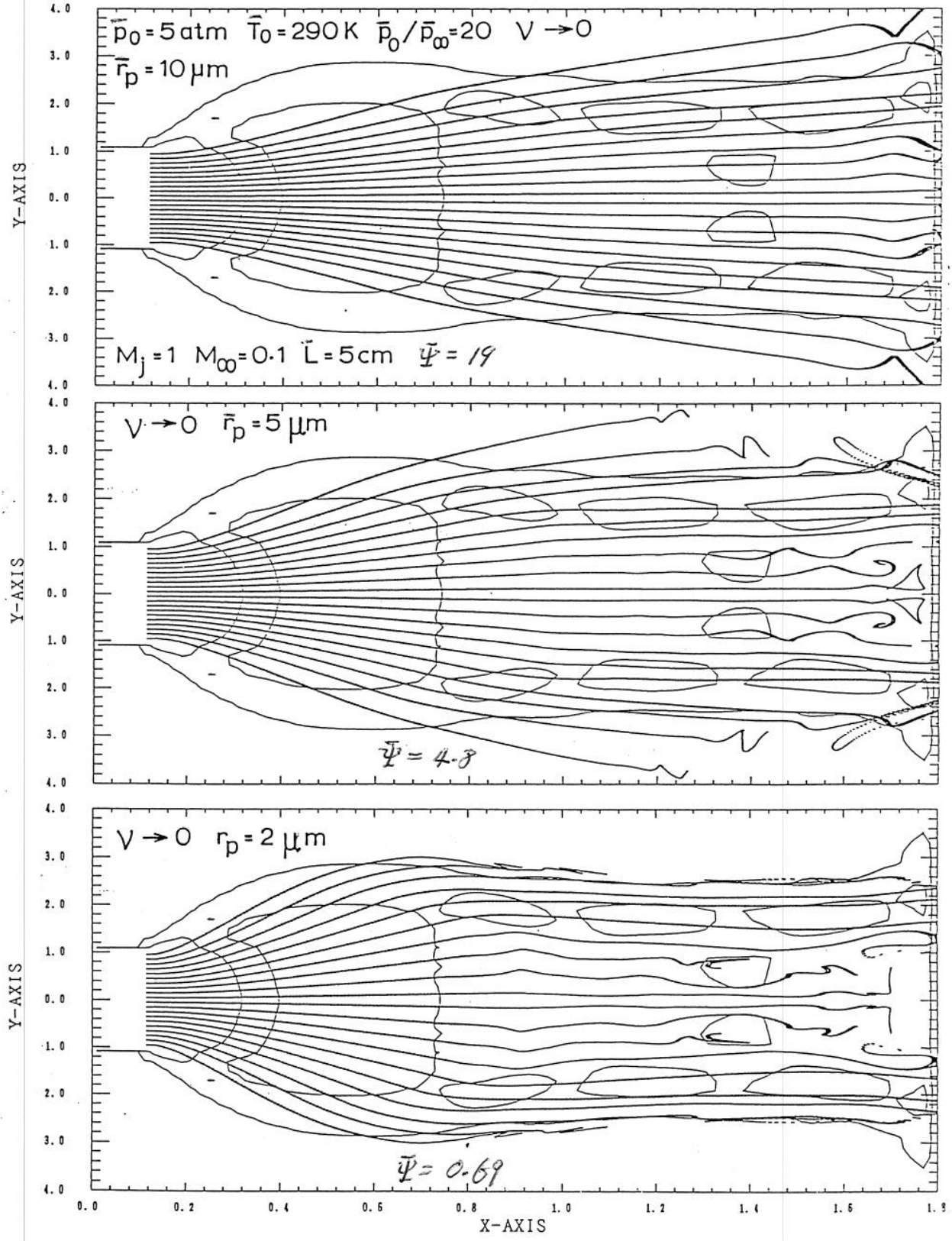

$\bar{p}_0 = 5$ atm $\bar{T}_0 = 290$ K $\bar{p}_0/\bar{p}_\infty = 20$ $V \to 0$
$\bar{r}_p = 10\,\mu$m
$M_j = 1$ $M_\infty = 0.1$ $\bar{L} = 5$cm $\bar{\Psi} = 19$
$V \to 0$ $\bar{r}_p = 5\,\mu$m
$\bar{\Psi} = 4.8$
$V \to 0$ $r_p = 2\,\mu$m
$\bar{\Psi} = 0.69$
Y-AXIS
Y-AXIS
Y-AXIS
X-AXIS
4.0
3.0
2.0
1.0
0.0
1.0
2.0
3.0
4.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

Fig. B-10-1

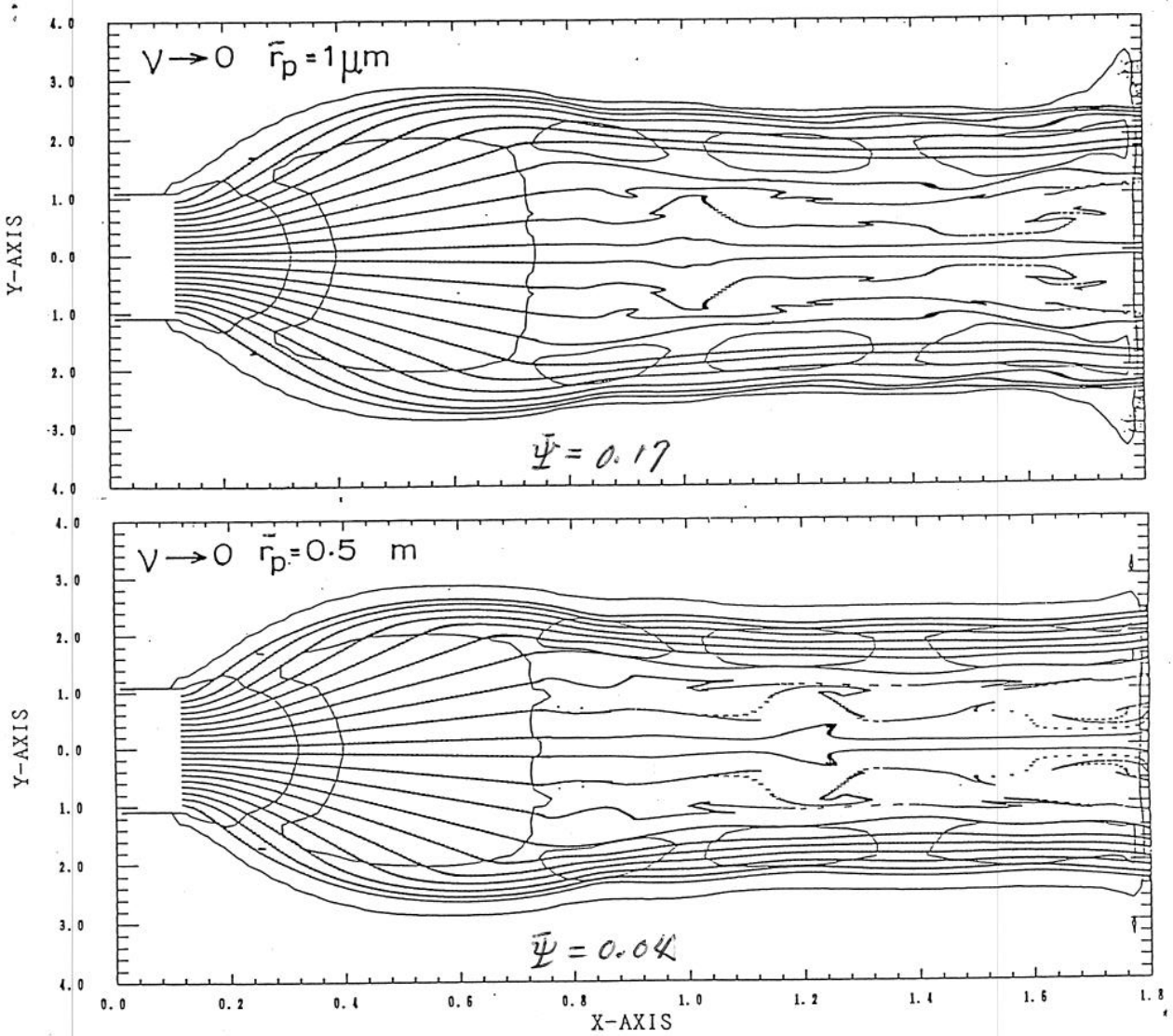

V → 0 r̄p = 1 μm
Ψ̄ = 0.17
V → 0 r̄p = 0.5 m
Ψ̄ = 0.04
Y-AXIS
X-AXIS
4.0
3.0
2.0
1.0
0.0
1.0
2.0
3.0
4.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

Fig. B-10-2

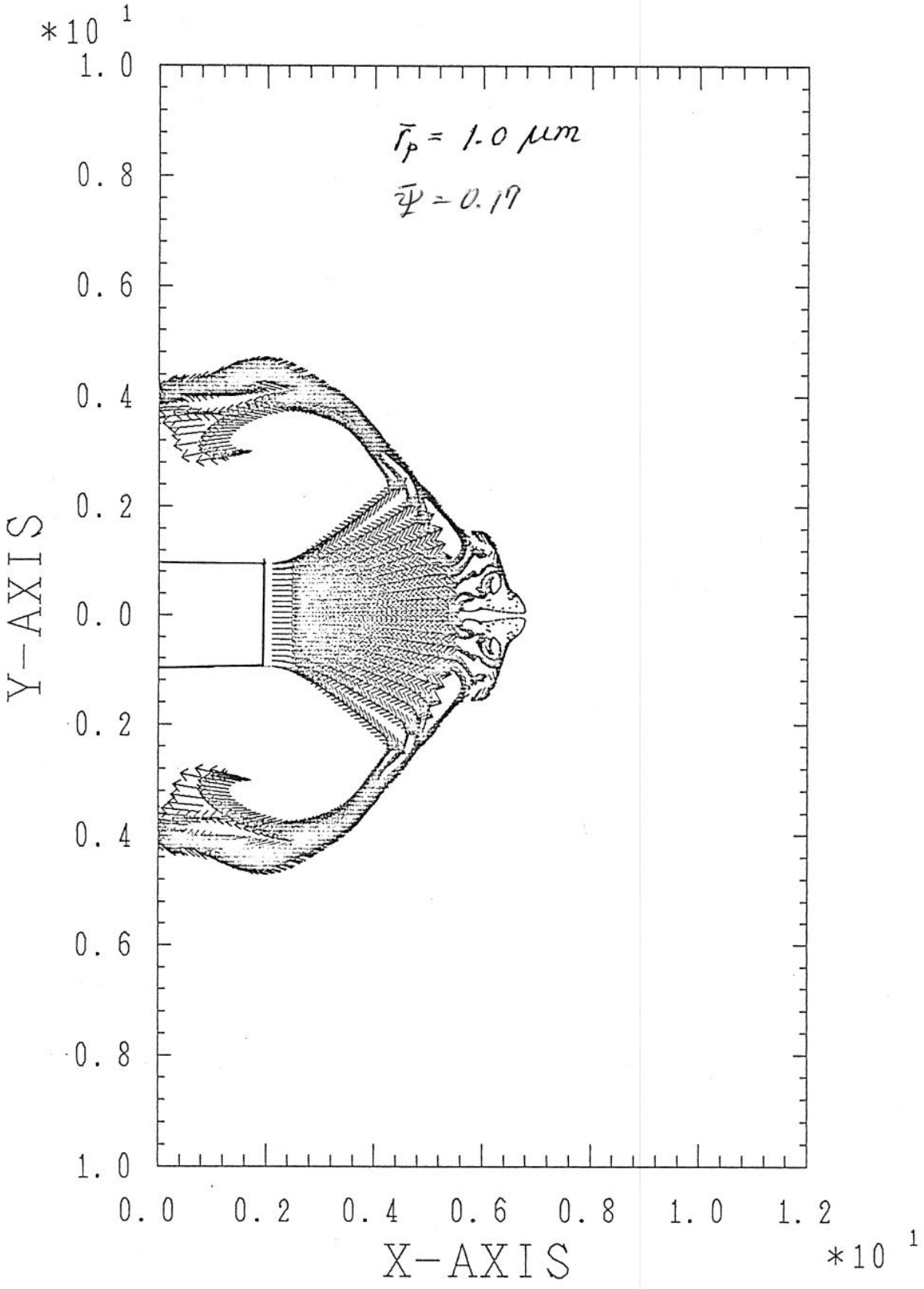

*10 1
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
Y-AXIS
$\bar{r}_p$ = 1.0 μm
$\bar{\Psi}$ = 0.19
0.0
0.2
0.4
0.6
0.8
1.0
1.2
X-AXIS
*10 1

Fig. B-11-1

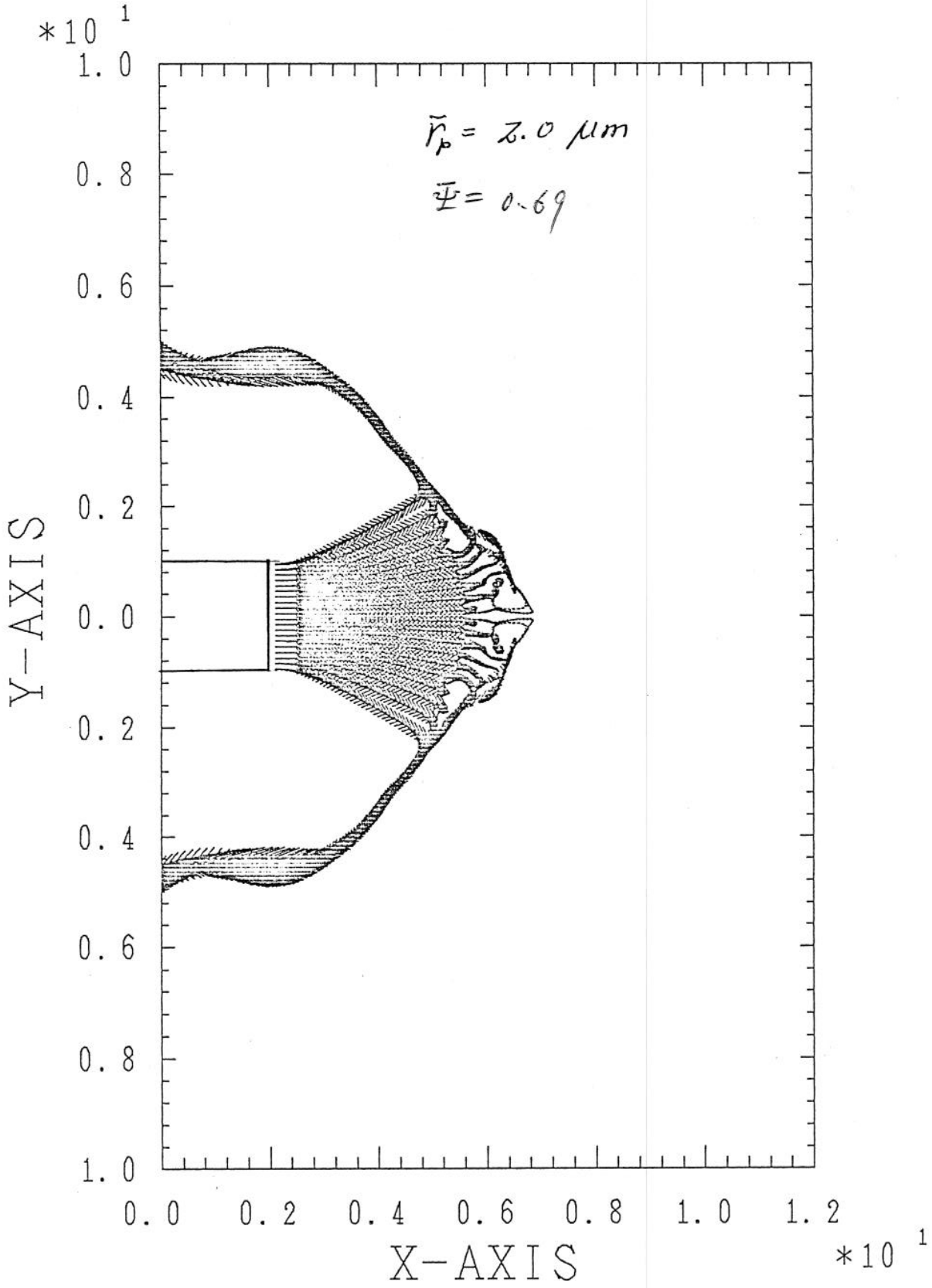

*10 1
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
Y-AXIS
$\bar{r}_p$ = 2.0 μm
$\bar{\Psi}$ = 0.69
0.0
0.2
0.4
0.6
0.8
1.0
1.2
*10 1
X-AXIS

Fig. B-11-2

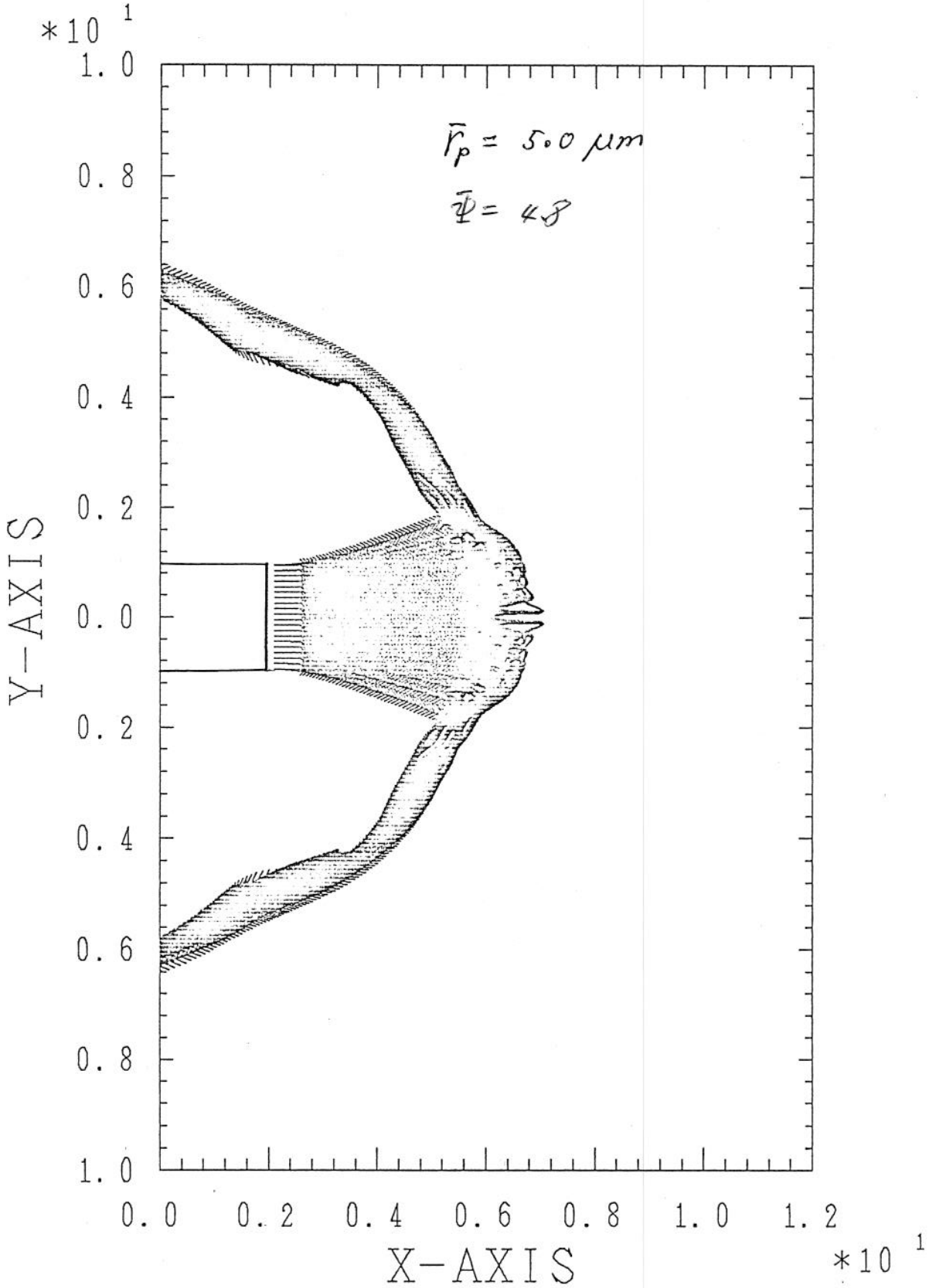

*10 1
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
Y-AXIS
$\bar{r}_p$ = 5.0 μm
$\bar{\Psi}$ = 43
0.0
0.2
0.4
0.6
0.8
1.0
1.2
X-AXIS
*10 1

Fig. B-11-3

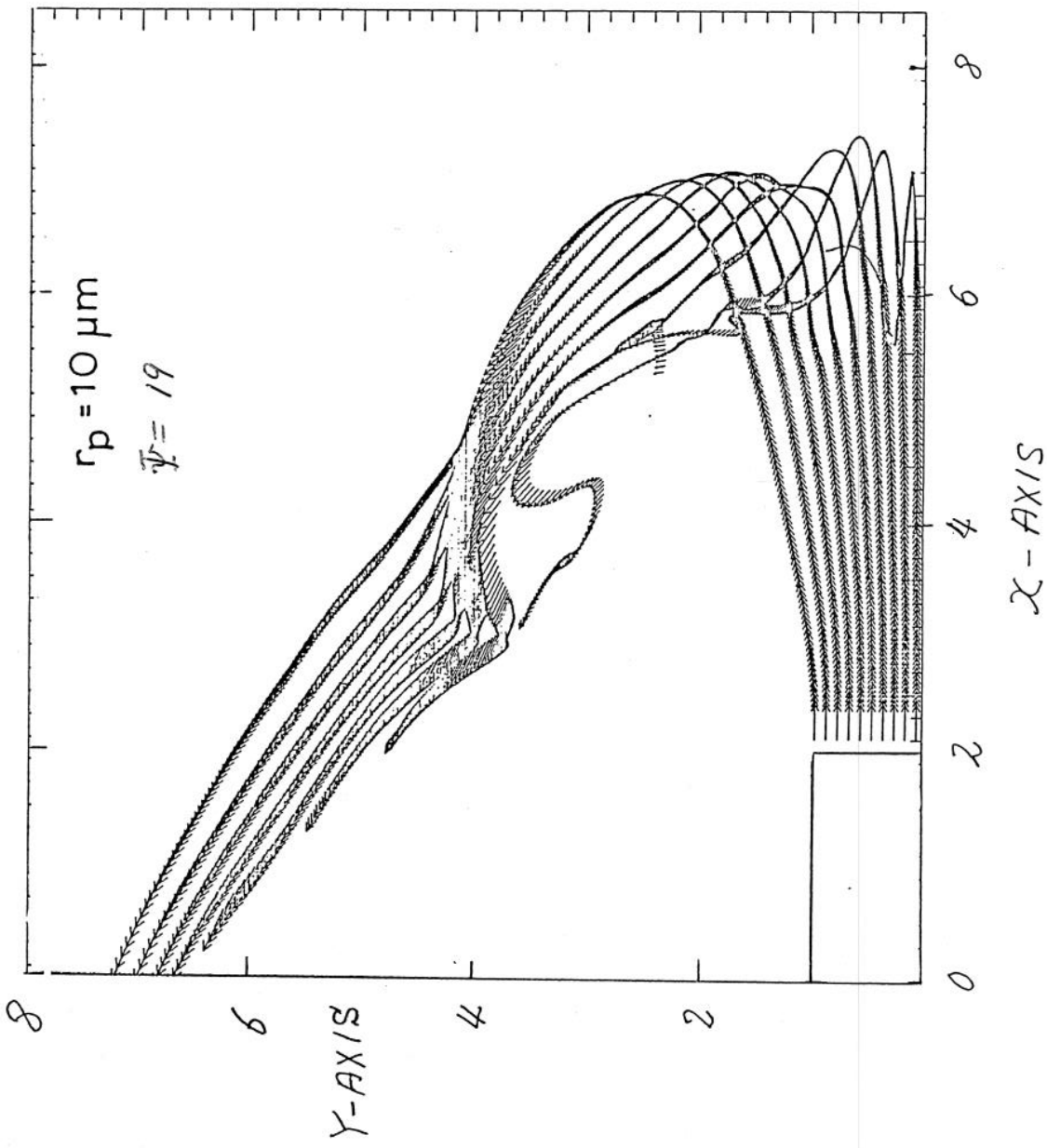


Fig. B-11-4

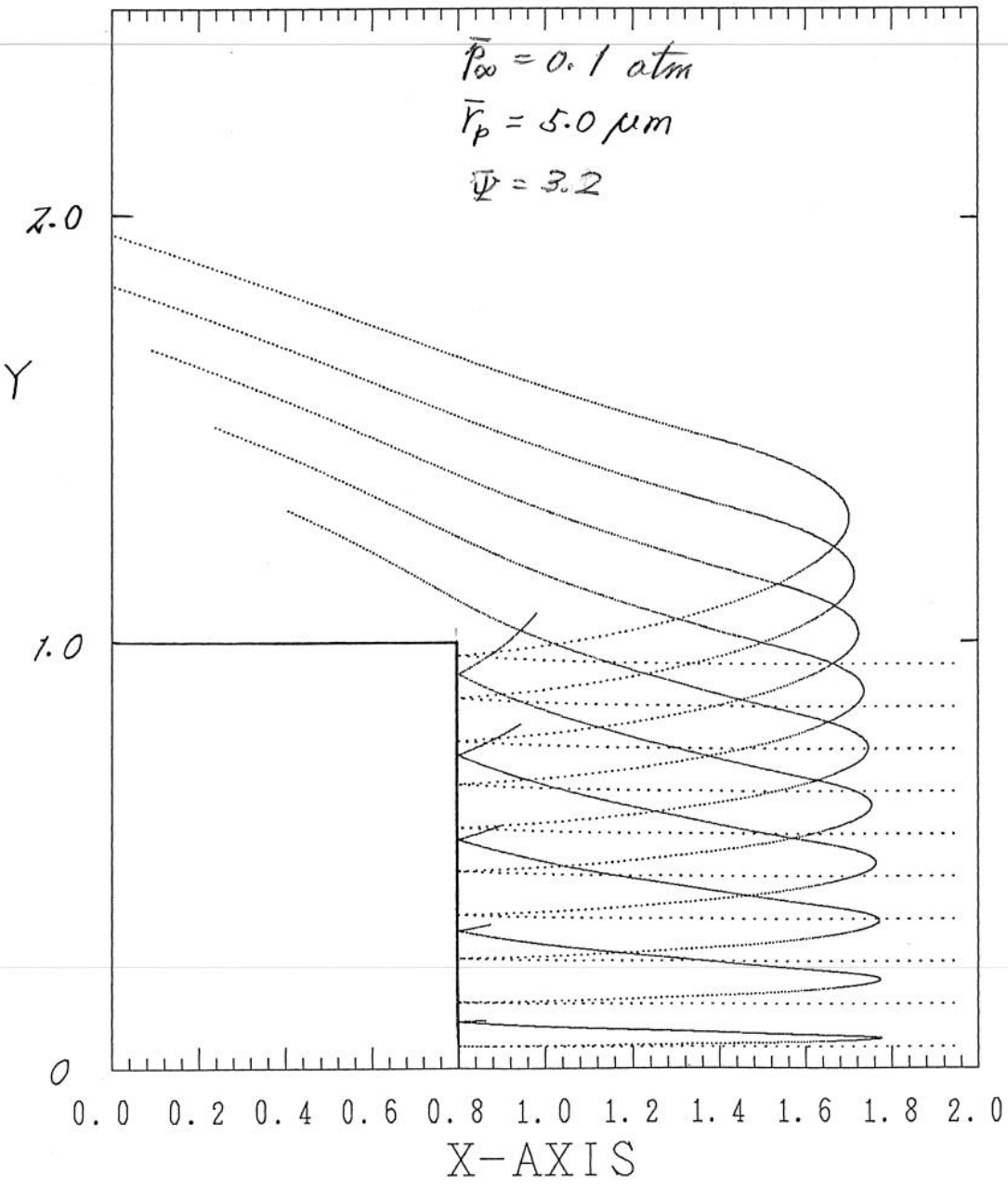

$\bar{P}_\infty = 0.1$ atm
$\bar{r}_p = 5.0\ \mu m$
$\bar{\Psi} = 3.2$
2.0
1.0
0
Y
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
X-AXIS

Fig. B-12

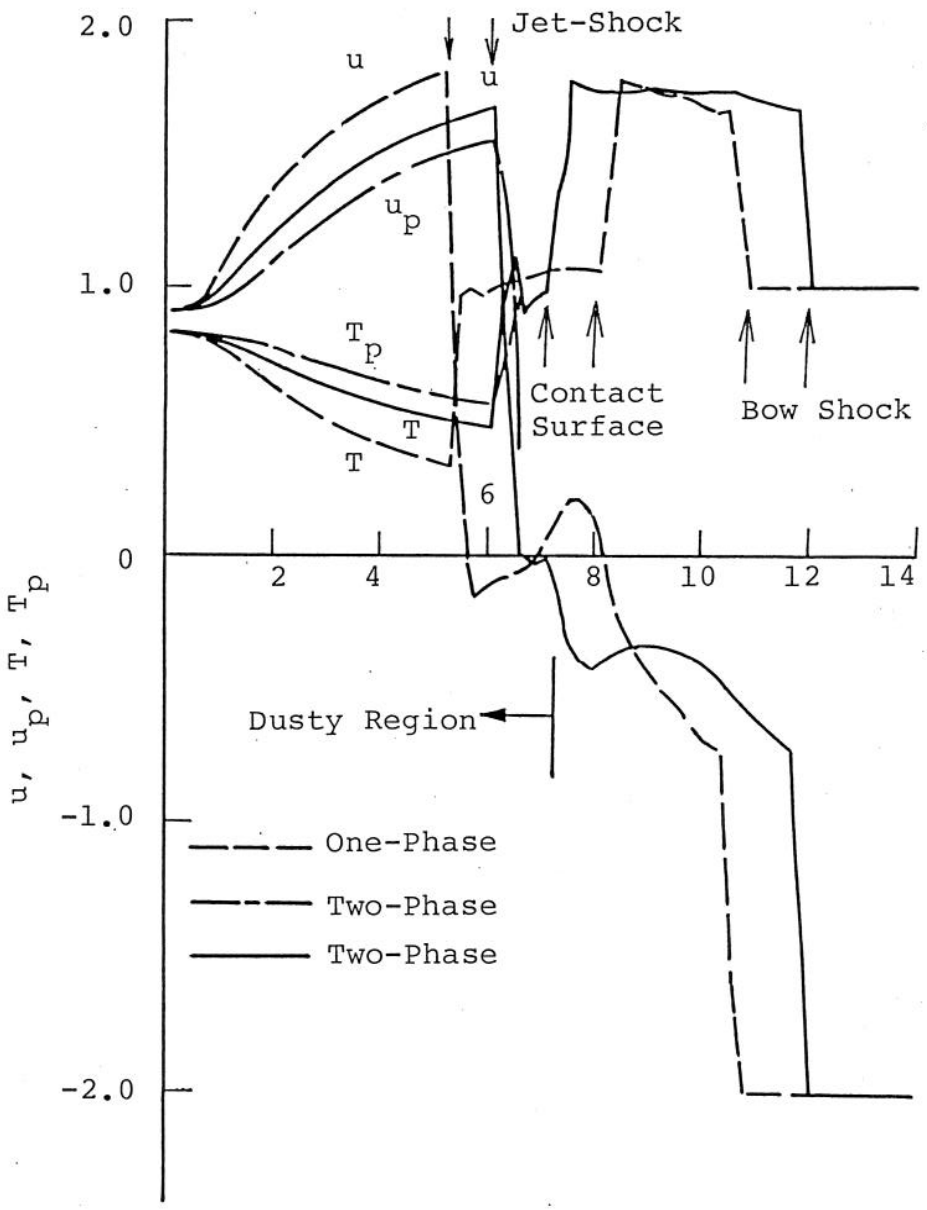
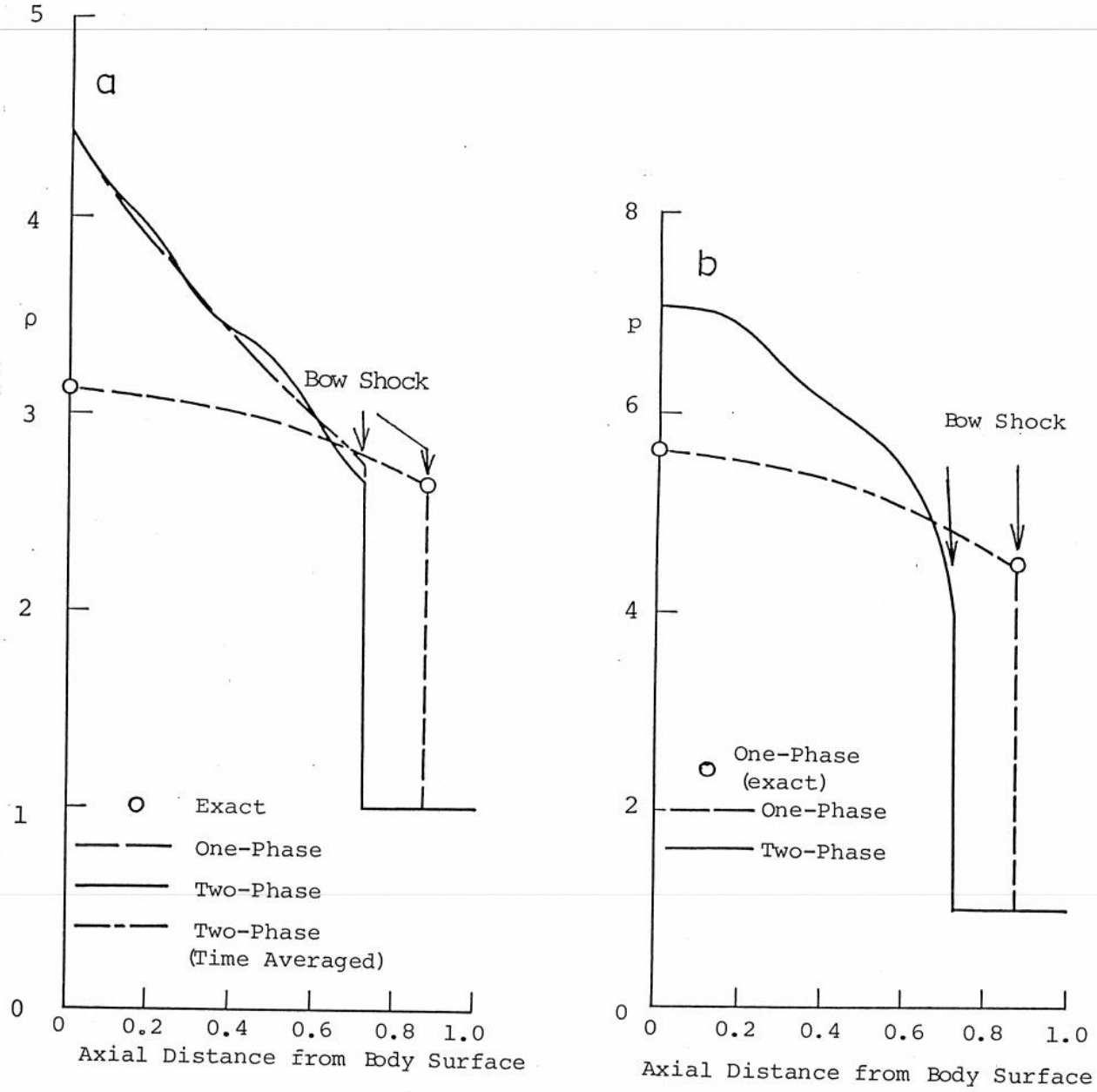
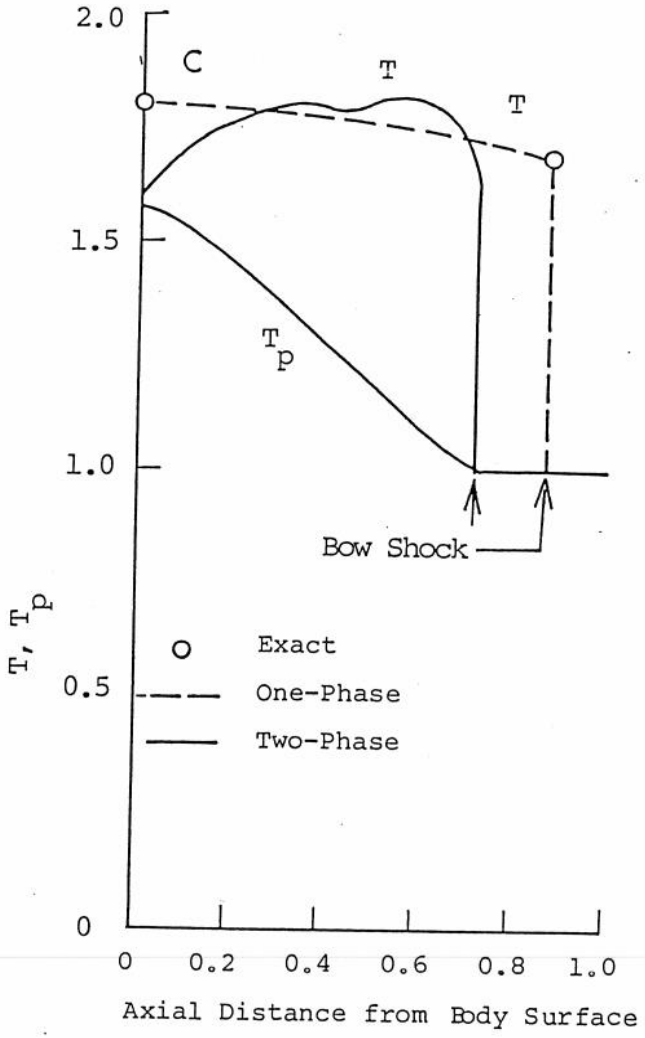

2.0
1.0
0
-1.0
-2.0
u, u_p, T, T_p
Jet-Shock
u
u
u_p
T_p
T
T
Contact Surface
Bow Shock
6
2
4
8
10
12
14
Dusty Region
One-Phase
Two-Phase
Two-Phase

Fig. B-14

Fig. B-15-1


a
5
4
3
2
1
0
p
Bow Shock
Exact
One-Phase
Two-Phase
Two-Phase
(Time Averaged)
0
0.2
0.4
0.6
0.8
1.0
Axial Distance from Body Surface
b
8
6
4
2
0
p
Bow Shock
One-Phase
(exact)
One-Phase
Two-Phase
0
0.2
0.4
0.6
0.8
1.0
Axial Distance from Body Surface


c
T
T
T_p
Bow Shock
Exact
One-Phase
Two-Phase
T, T_p
2.0
1.5
1.0
0.5
0
0
0.2
0.4
0.6
0.8
1.0
Axial Distance from Body Surface

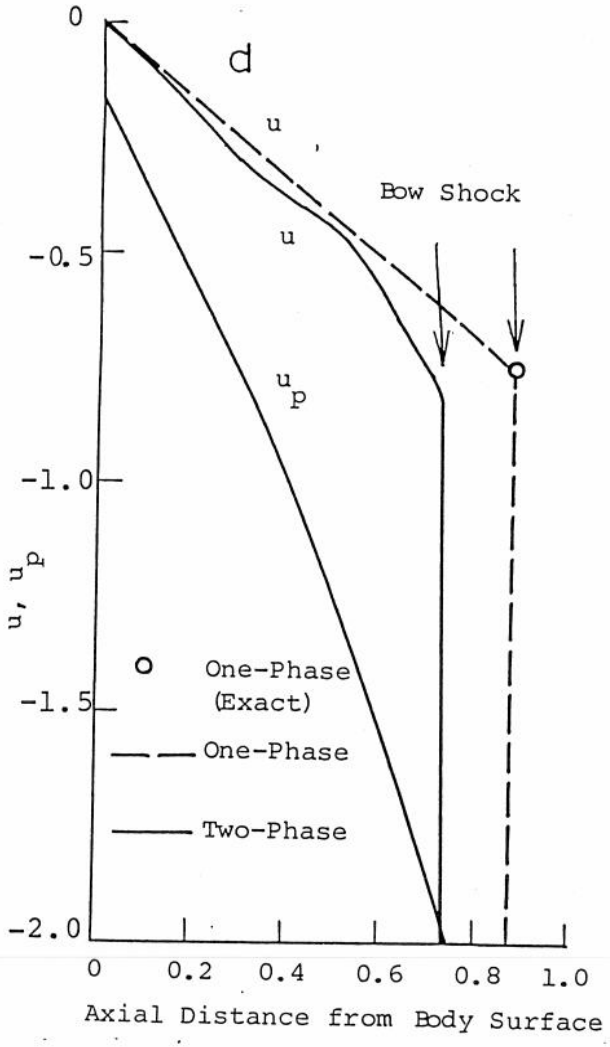
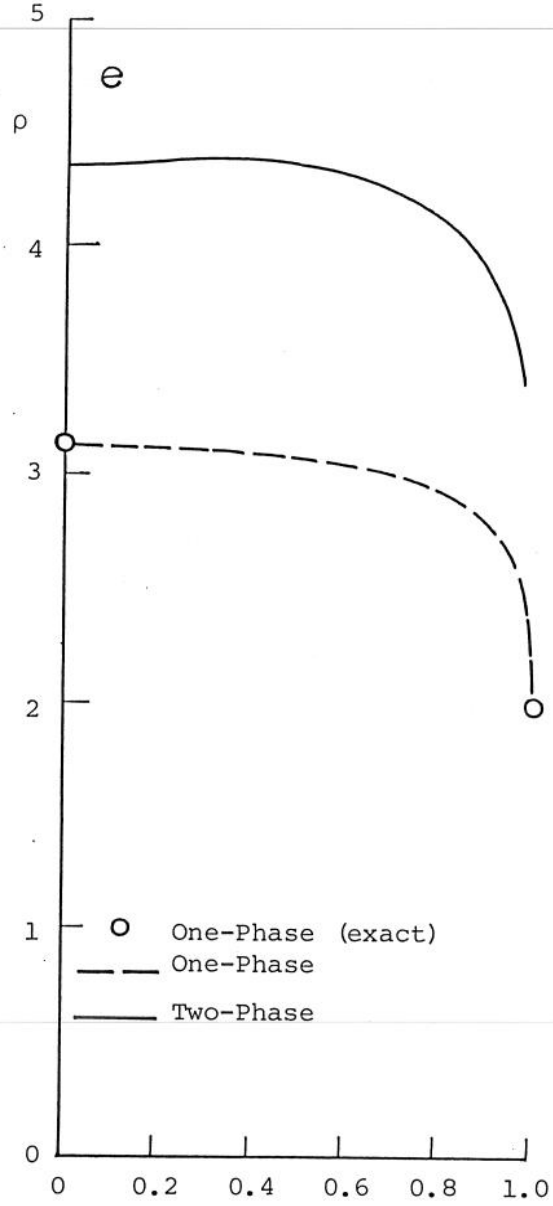
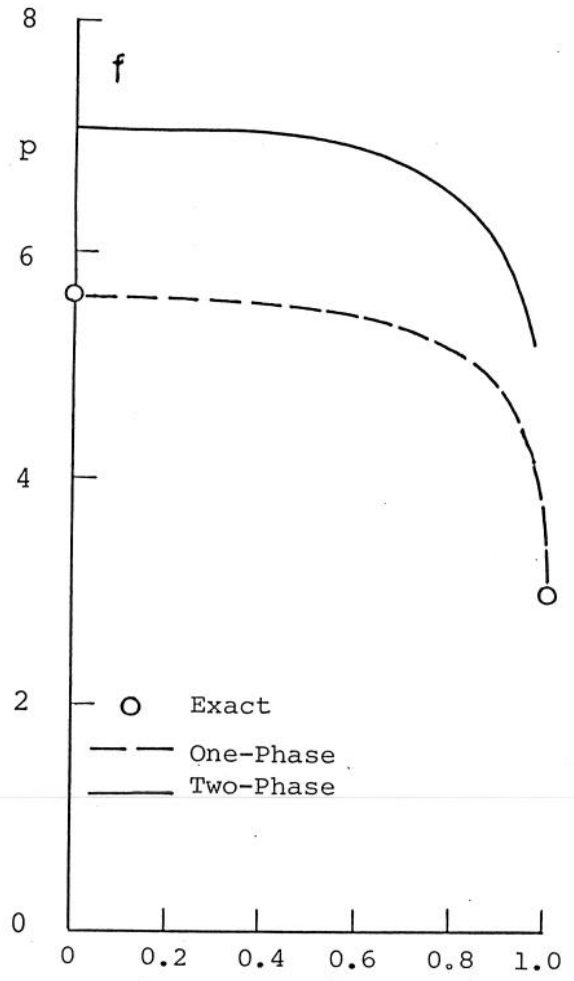

d
u
u
u_p
Bow Shock
One-Phase
(Exact)
One-Phase
Two-Phase
u, u_p
0
-0.5
-1.0
-1.5
-2.0
0
0.2
0.4
0.6
0.8
1.0
Axial Distance from Body Surface

Fig. B-15-2

Fig. B-15-3


e
ρ
5
4
3
2
1
0
0
0.2
0.4
0.6
0.8
1.0
One-Phase (exact)
One-Phase
Two-Phase
Radial distance along Body Surface


f
p
8
6
4
2
0
0
0.2
0.4
0.6
0.8
1.0
Exact
One-Phase
Two-Phase
Radial Distance along Body Surface

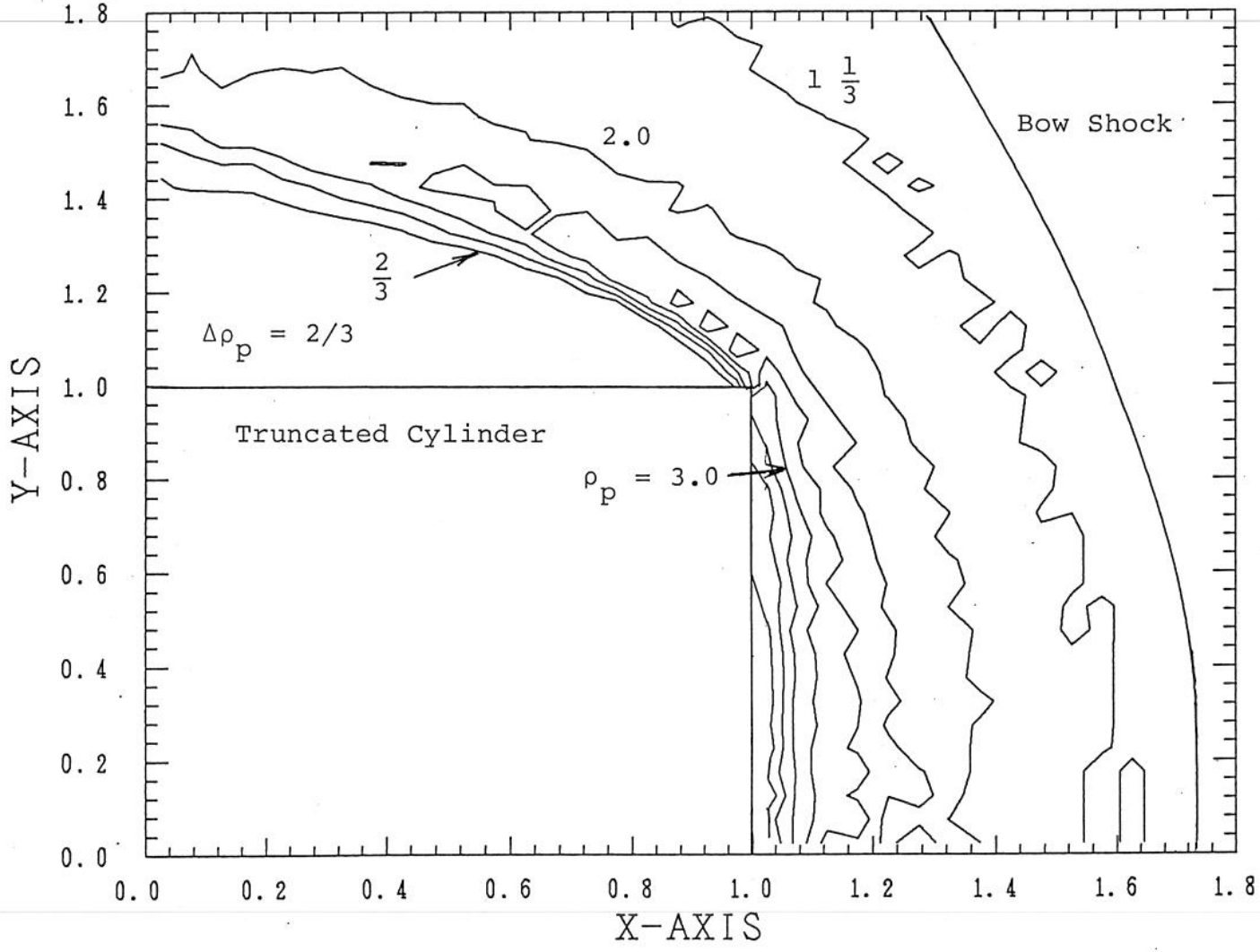

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Y-AXIS
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
X-AXIS
1 1/3
2.0
Bow Shock
2/3
Δρp = 2/3
Truncated Cylinder
ρp = 3.0

Fig. B-16

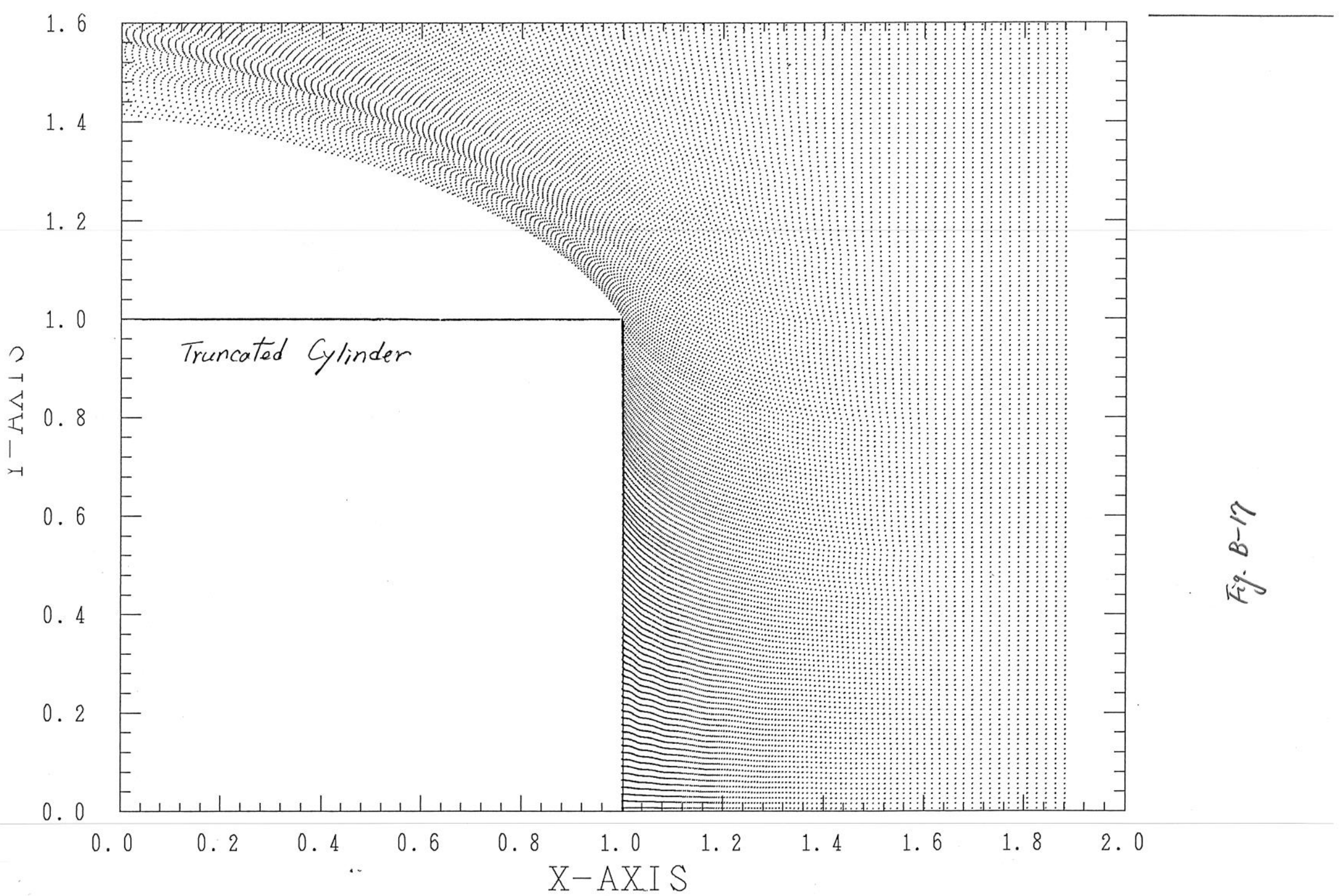

Truncated Cylinder
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Y-AXIS
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
X-AXIS

Fig. B-17