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DEVELOPING CONVECTION ABOVE A FINITE HORIZONTAL SURFACE

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Abstract

This paper reports the results of an experimental study of the initiation of convection above a suddenly heated horizontal surface of finite extent. The phenomenon of flow initiation in fluid layers is of both engineering and geophysical interests (Mollendorf et al., 1984 and Olson et al., 1988). While there are a number of previous studies both theoretical (Currie, 1967 and Kim and Kim 1986) and experimental (Nielsen and Sabersky, 1973, Mollendorf et al., 1984, and Kukalka and Mollendorf, 1988) the present study is the first that deals specifically with surfaces of finite extent.

The experimental apparatus consists of a transparent enclosure with a square planform measuring 55.9 cm by 55.9 cm. An electrically heated strip, with a width equal to one-fourth of the length of a side of the enclosure, is centered on the lower inside surface of the enclosure. The depth of the fluid layer is the same as the width of the heated strip. The top of the fluid layer is bounded by a constant temperature plate. The working fluid is a commercial corn sweetener 42/43 corn syrup. Details of the experimental apparatus and the working fluid can be found in (Chu and Hickox, 1988).

Initially the fluid layer is at a uniform temperature. At time zero, a constant energy input is applied to the heated strip, while maintaining the top surface at the initial temperature. Observations are made of the transient flow field, heater surface temperature and heat flux distribution.

The results of three experiments with three different heat fluxes are reported here; they are designated as Cases A, B, and C in Figure 1. Initially the temperature of the heated surface follows closely the conduction solution. With the initiation of convection, the response curve departs smoothly from the conduction solution. A temperature overshoot followed by a gradual approach to steady state is observed. The same data plotted in log-log scales in Figure 2 show that the transient responses are essentially similar.

Shown in Figure 3 is a series of time-lapse photographs illustrating the development of the flow field for Case A, q = 19.0 mW/cm^2. The photographs are 4.5-min time exposures taken 5 min apart. Incipient fluid motion (streaks) can be observed in the horizontal direction near the edge of the heated strip at forty minutes into the experiment; long before the temperature response shows any significant departure from the conduction

solution. With time, the development of two counter-rotating cells, driven by a central plume rising from the heated strip, can be clearly observed. At incipient motion, the centers of the cells are directly above the edges of the heated strip; they move progressively closer as the central plume develops. When the cell distance reaches a minimum, they begin to rise from the heated strip and move apart horizontally. The upward motion is stopped by the presence of the top surface; the cells eventually settle downward to steady state positions. As shown in Figure 4, there is a close correspondence between the movement of the cells and the temperature response of the heated surface.

Approximate heat flux distributions over the heated strip are obtained using slit deflection shadowgraph. The method is based on the deflection of a slit of parallel light by the thermal boundary layer. The amount of deflection is a measure of the local heat flux. A typical sequence of results is shown in Figure 5. The heat flux is uniform during the conduction phase. At incipient motion, a slight depression is observed near the edge of the heated strip. The movements of the two depressions replicates exactly the movements of the cells. Eventually, the two depressions merge into one at the closest approach of the two cells.

The conventional method of representing the results of linear stability analyses for the onset of convection uses the Rayleigh number and a dimensionless heat flux, H, based on the layer depth, D:

$$Ra = \frac{g\beta}{\nu\alpha} \Delta T D^3; \quad H = \frac{g\beta}{\nu\alpha} \frac{q}{k} D^4 \tag{1}$$

where q is the heat flux at the lower surface. As first observed by Nielsen and Sabersky (1973) for high heating rates (or large spacing) the onset of convection takes place before the thermal wave penetrates the fluid layer. Therefore, the onset of convection should be independent of the layer depth and Ra_c should be proportional to $H^{3/4}$:

$$Ra_c = CH^{3/4} \tag{2a}$$

For the present experiment, we follow the Kim and Kim (1986) criteria by defining the onset of convection to be at the "minimum Nusselt Number" or the "maximum temperature." The present data is found to be well represented by an $H^{3/4}$ correlation, Figure 6.

$$Ra_c = 3.82\ H^{3/4} \tag{2b}$$

Properties used in the correlation are evaluated at a bulk temperature calculated from the semi-infinite conduction temperature profile. The correlation is in excellent agreement with the Nielsen and Sabersky data for "infinite (in width) layers."

By substituting the relation between ΔT and q for the semi-infinite conduction solution into equations (1) and (2a), we are able to show the deep layer correlation to be completely equivalent to Howard's (1964) theory of conduction boundary layer instability:

$$Ra_{c,\delta} = \frac{g\beta}{\nu\alpha} \Delta T_{max} \delta^3 = C^4 (\frac{\pi}{2})^3 (\Delta T_{max,cd}/\Delta T_{max})^3 = \text{constant} \qquad (3a)$$

$$\delta = \sqrt{\pi \ \alpha \ \tau_{max}} \qquad (3b)$$

where the last term in Equation (3a) accounts for the fact that the temperature of the heated surface deviates from the conduction solution as the surface temperature approaches T_{max}; the subscript cd denotes conduction solution. The resulting critical Rayleigh number based on the thermal boundary layer thickness is then calculated to be 1000. Alternately, the critical Rayleigh number can be determined by calculating the thermal boundary layer thickness, δ. The critical Rayleigh number thus calculated are 1041, 1053 and 1259 for cases A, B, and C respectively. The average value of 1118 is about 12% higher than the estimate based on the deep layer correlation. The main source of discrepancy is due to the fact that the heated strip does not follow the semi-infinite solution at small times.

Because the onset of convection is controlled by the conduction boundary layer thickness, the critical Nusselt number based on the layer thickness was found to be essentially constant, 1.70, 1.75 and 1.79 for Cases A, B, and C respectively. Furthermore, similar to infinite layers the ratio of the cell distance to the thermal boundary layer thickness at the onset of convection was also found to be essentially constant having a value of 1.95 for Case A and 1.99 for Case B.

By using complementary methods of observation, we are able to illustrate in detail the sequence of events occurring during the initiation of convection above a finite horizontal surface. The results share many common features with infinite layers. Perhaps, one can argue that the present experiment simply isolates a single "unit" from an infinite number of repeating "units" for an "infinite layer." Of course, all experiments are finite, it is entirely likely that the first instability could have occurred near the edge of an enclosure out of the "normal" field of observation in other experiments also. The "edge instability" observed by Kukalka and Mollendorf, 1988) is a good example.

REFERENCES:

Currie, I. G., 1967, "The Effect of Heating Rate on the Stability of Stationary Fluids," J. Fluid Mechanics., Vol. 29, Part 2, pp 337-349.

Chu, T. Y. and Hickox, C. E., 1988, "Thermal Convection with Large Viscosity Variation in an Enclosure with Localized Heating," ASME HTD Vol. 99 Natural Convection in Enclosures 1988. R. S. Figliola and P. G. Simpkins, Editors.

Howard, L. N., 1964, "Convection at High Rayleigh Number," Proc. 11th Cong. Appl. Mech. H. Gortler Springer, Editor, Berlin.

Kukulka, D. J. and Mollendorf, J. C., 1988, "An Experimental Study of Transient Transport Near Heated Horizontal Surface," Experimental Heat Transfer, Fluid Mechanics and Thermodynamics. R. K. Shah, E. N. Ganic, and K. T. Yang, Editors, Elsevier Science Publishing Co.

Mollendorf, J. C., Arit H. and Ajiniran, 1984, "Developing Flow and Transport Above a Suddenly Heated Horizontal Surface in Water," Int. J. Heat Mass Transfer, Vol. 27, NO. 2, pp 273-289.

Kim, K. M. and Kim, M. U., 1986, "The Onset of Natural Convection in a Fluid Layer Suddenly Heated From Below," Int. J. Heat and Mass Transfer, Vol. 29, No 2, pp 193-201.

Nielsen, R. C. and Sabersky, R. M., 1973 "Transient Heat Transfer in Benard Convection," Int. J. Heat and Mass Transfer, Vol. 16, pp 2407-2420.

Olson, P., Schubert, G. and Anderson, C., 1988, "Plume Formation and Lithosphere Erosion Comparison of Laboratory and Numerical Experiments," J. G. R. Vol. 93, B12, pp 15065-15084.

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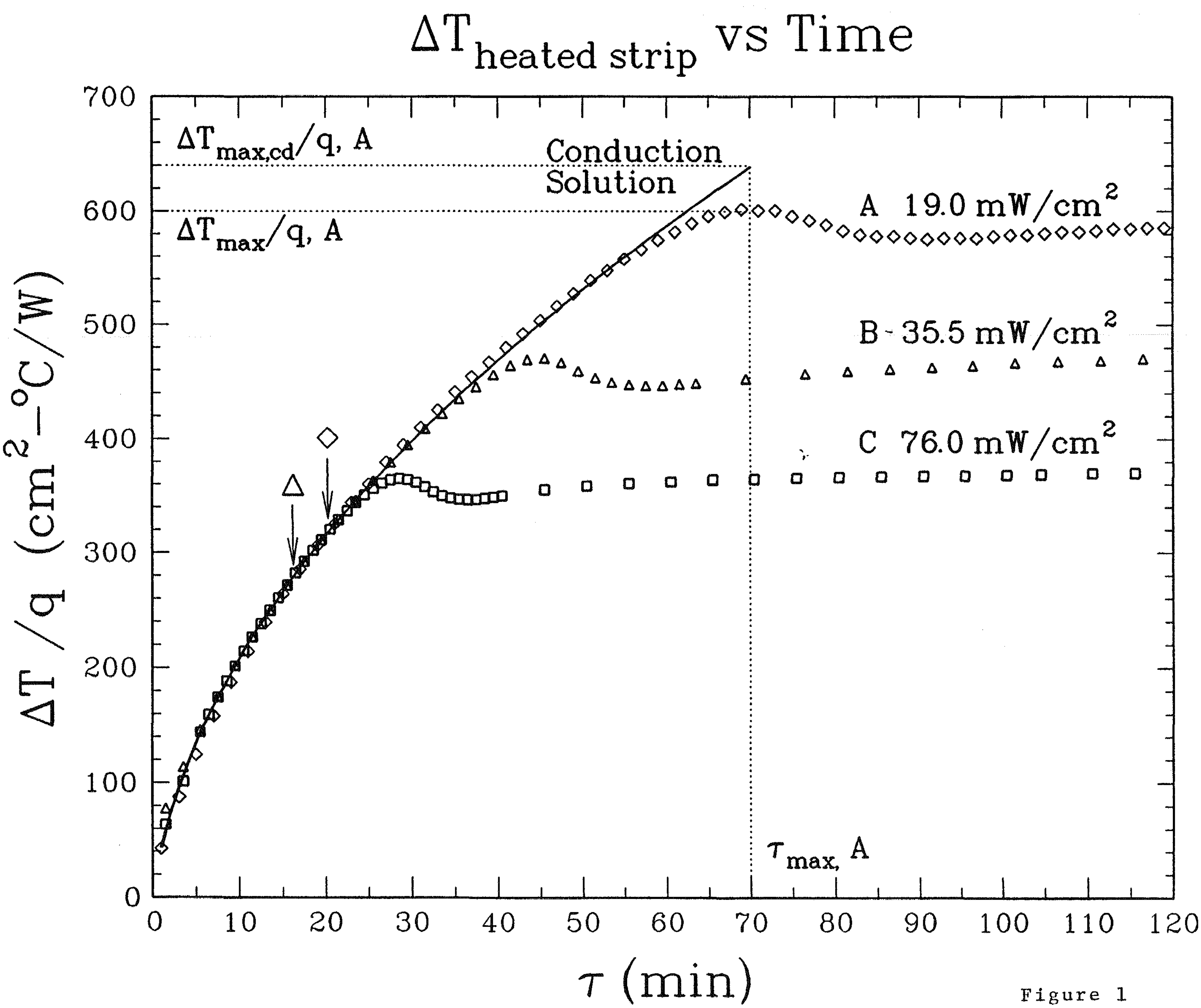

ΔT heated strip vs Time
ΔT max,cd/q, A
ΔT max/q, A
Conduction Solution
A 19.0 mW/cm²
B 35.5 mW/cm²
C 76.0 mW/cm²
τ max, A
ΔT /q (cm²-°C/W)
τ (min)
0
100
200
300
400
500
600
700
10
20
30
40
50
60
70
80
90
100
110
120

Figure 1

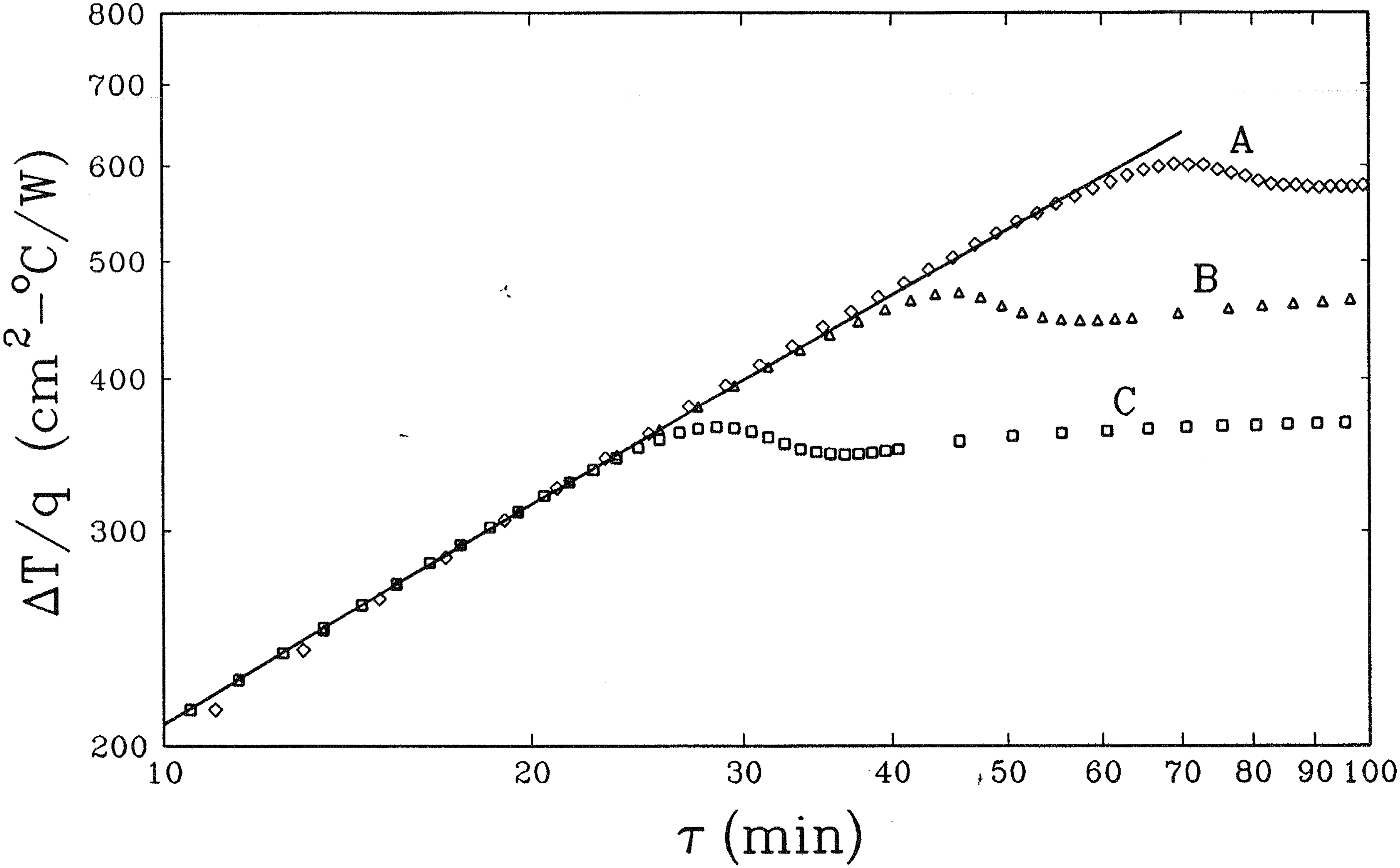
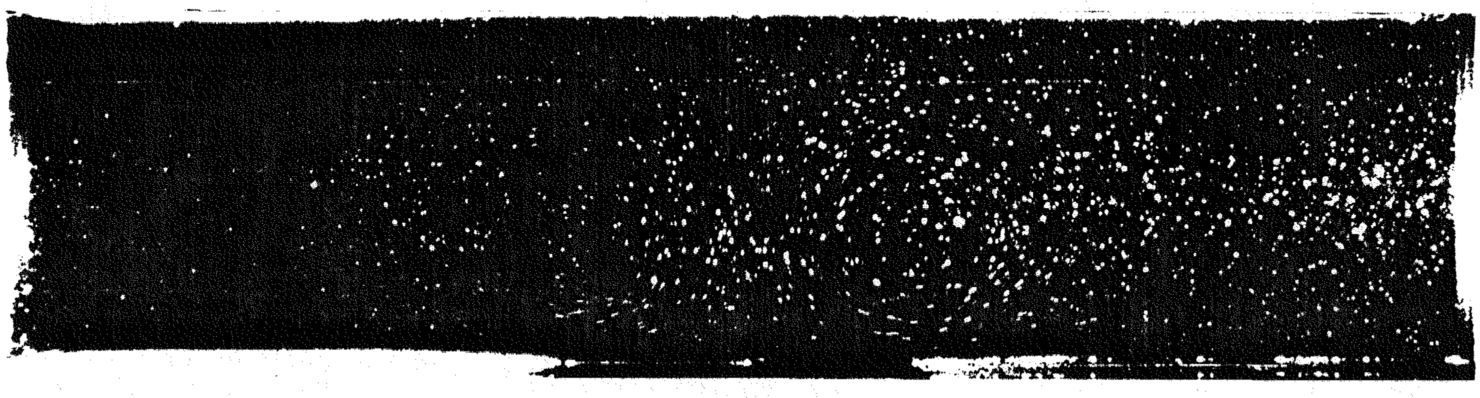

800
700
600
500
400
300
200
10
20
30
40
50
60
70
80
90
100
A
B
C
ΔT/q (cm²-°C/W)
τ (min)

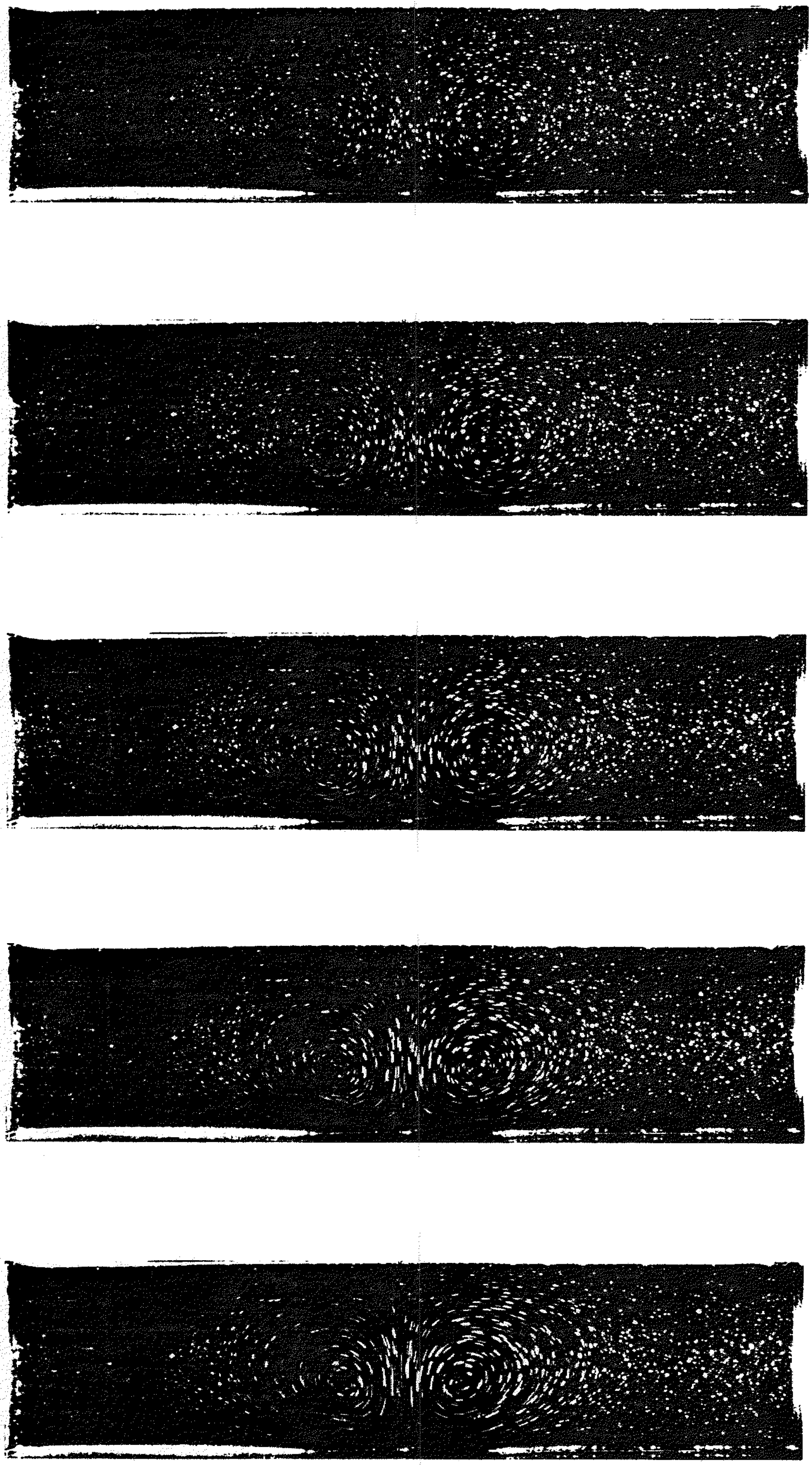
Figure 2

Initial State



40

Figure 3



45

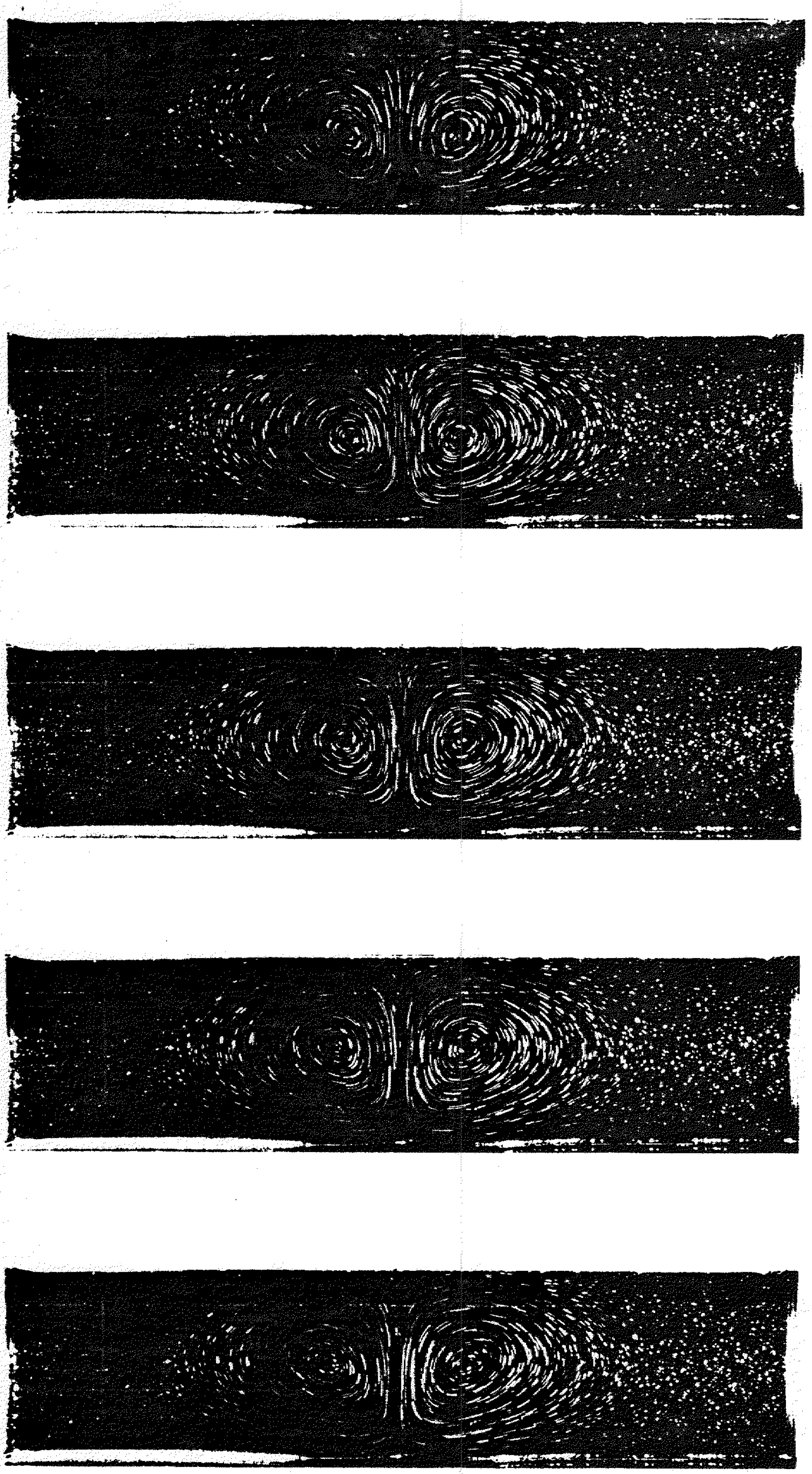
50

55

60

65

Figure 3 (Cont'd)



70, T_{max}

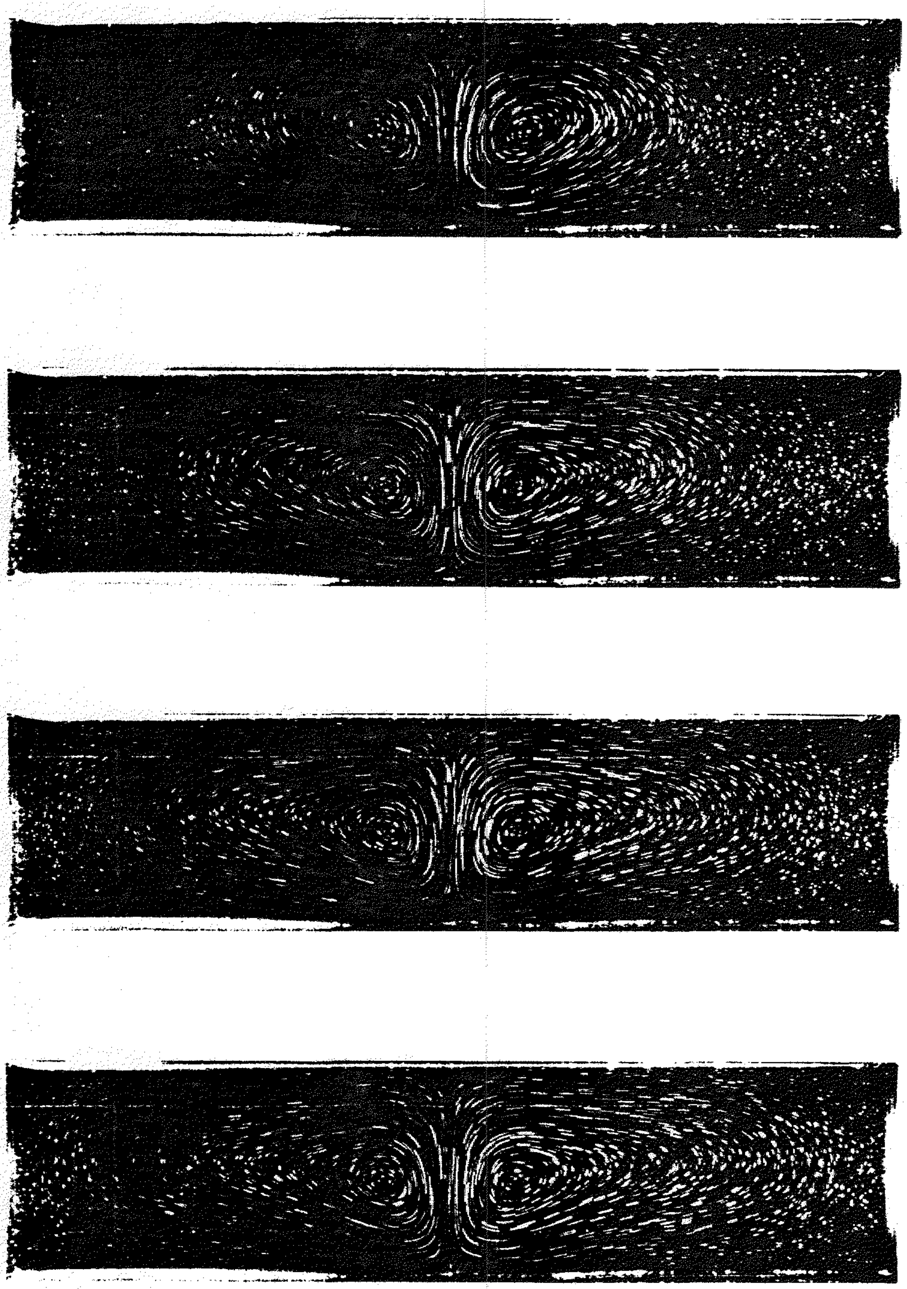
75

80

85

90, T_{min}

Figure 3 (Cont'd)



95

120

145

170

Figure 3 (Cont'd)

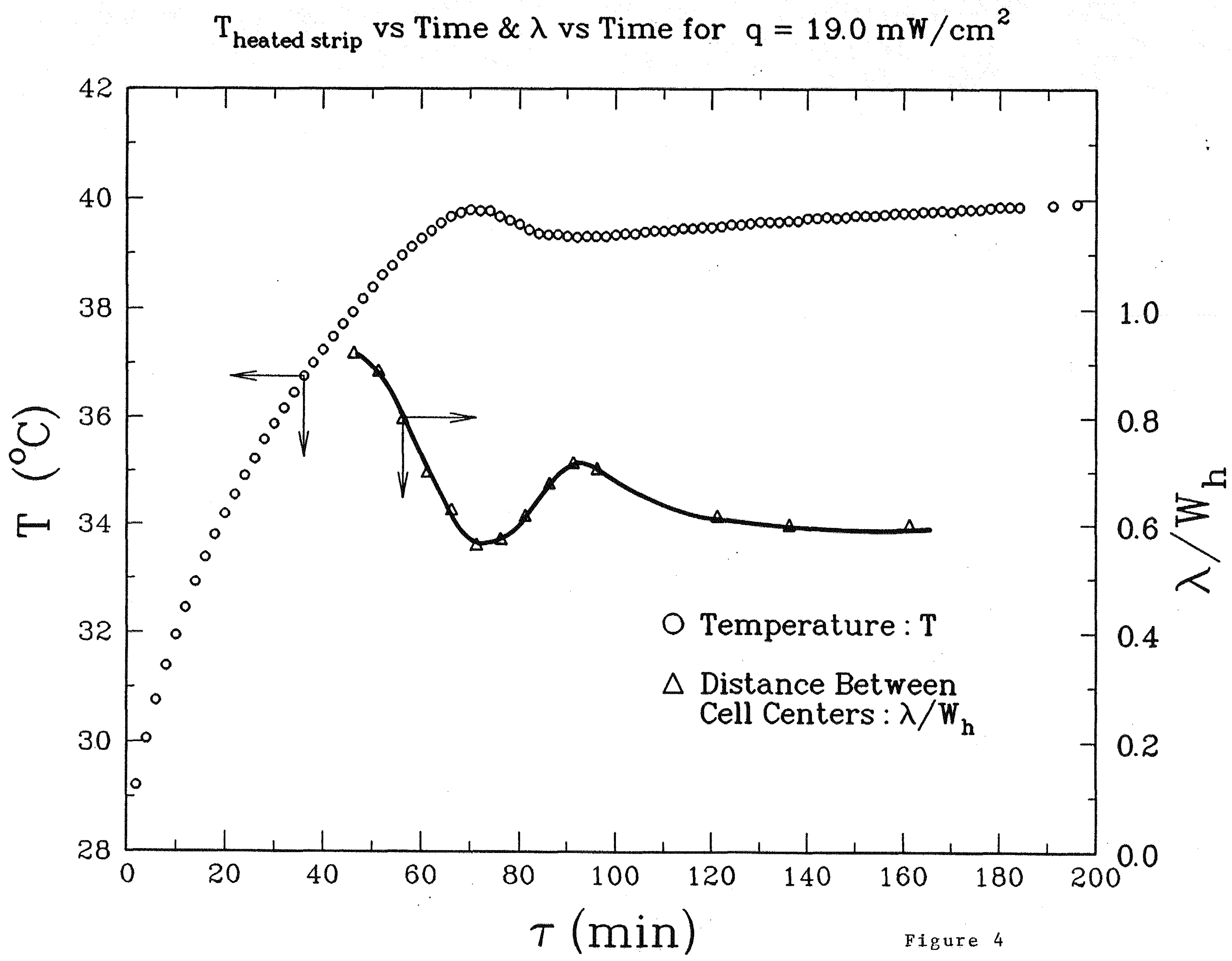

$T_{heated\ strip}$ vs Time & λ vs Time for q = 19.0 mW/cm^2
42
40
38
36
34
32
30
28
T (°C)
0
20
40
60
80
100
120
140
160
180
200
τ (min)
1.0
0.8
0.6
0.4
0.2
0.0
λ/W_h
Temperature : T
Distance Between Cell Centers : λ/W_h

Figure 4

Nu DISTRIBUTION ON HEATED STRIP USING SLIT DEFLECTION SHADOWGRAPH

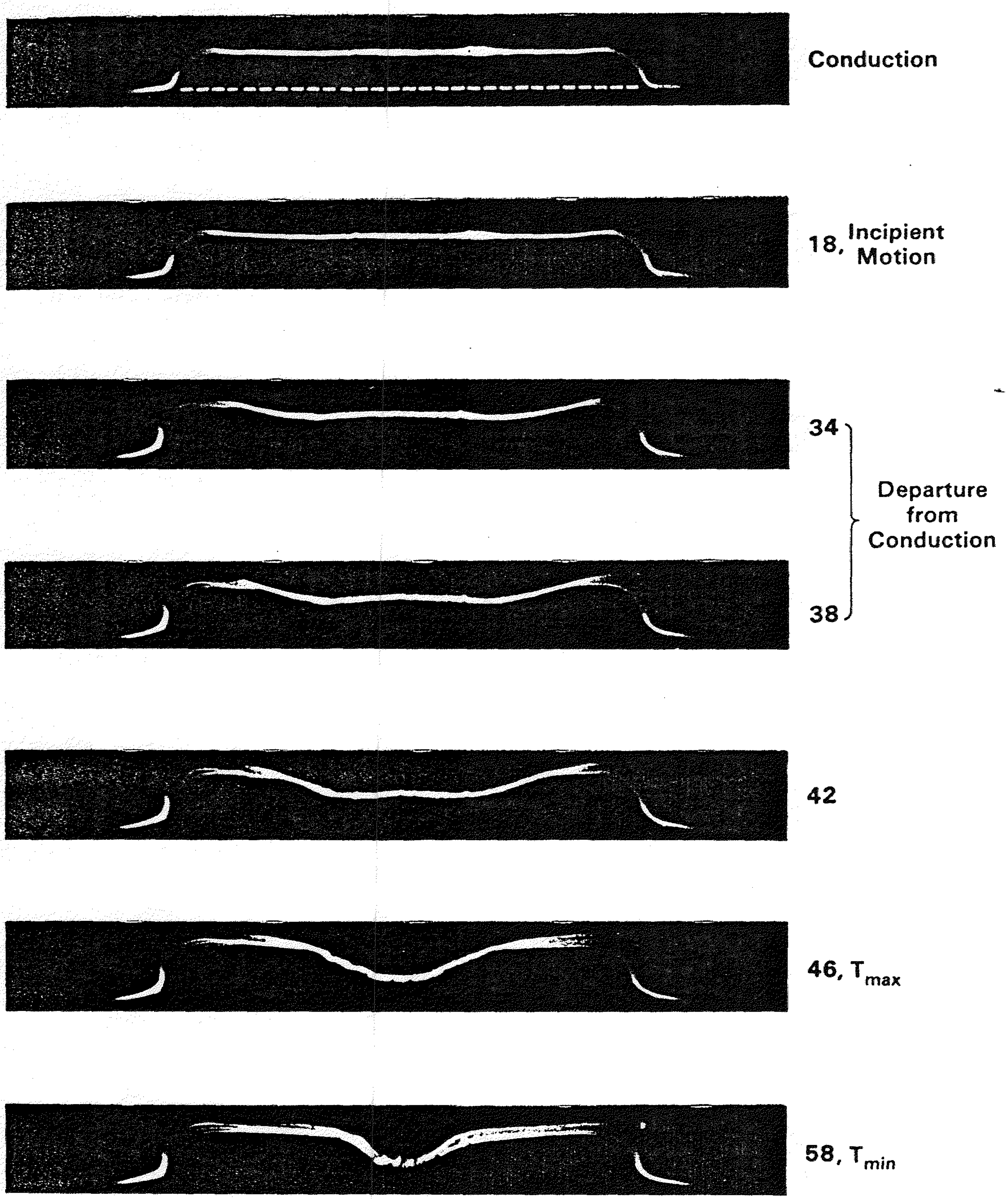
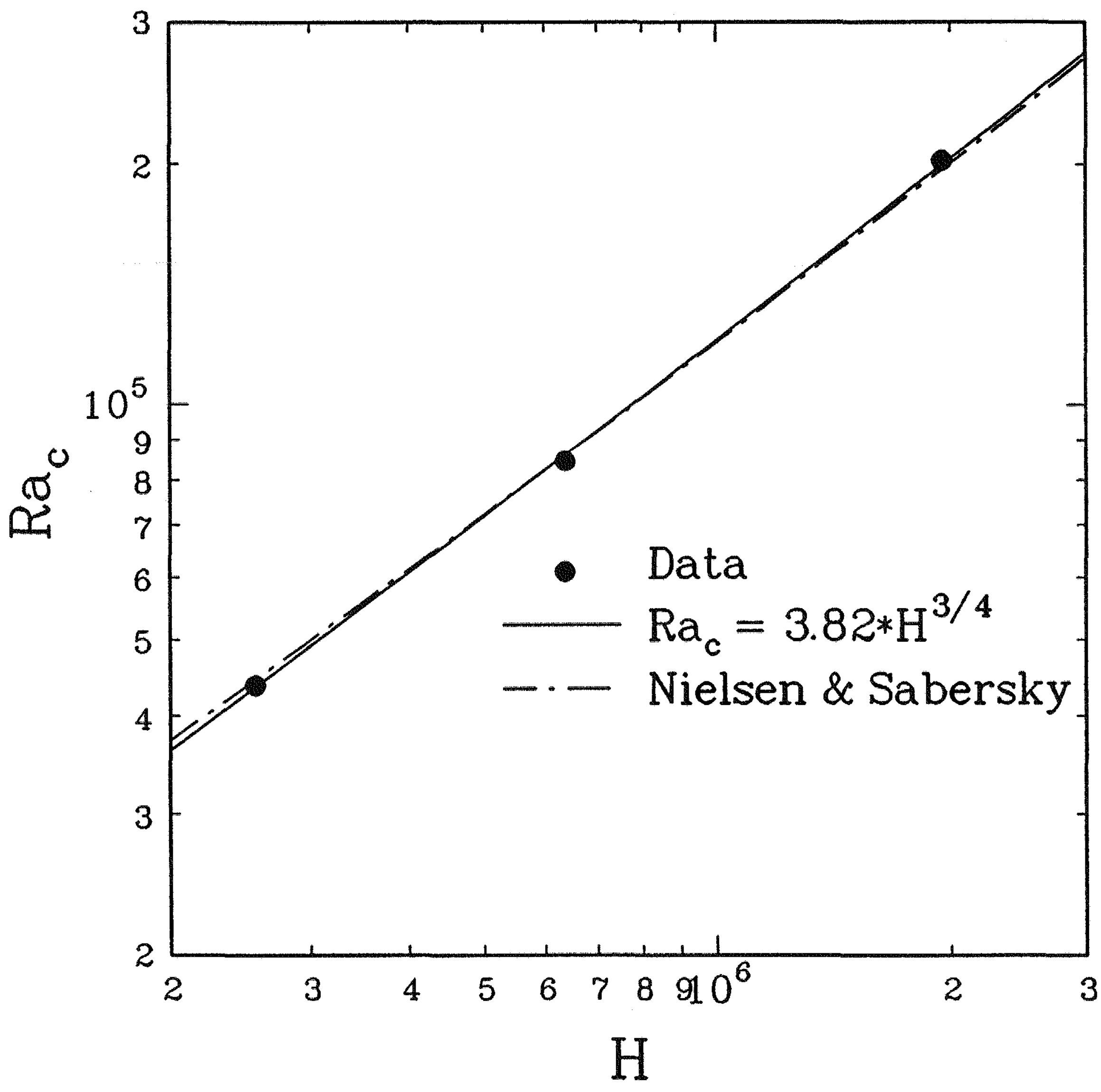


Figure 5



Data
$Ra_c = 3.82*H^{3/4}$
Nielsen & Sabersky
Ra_c
H
3
2
10^5
9
8
7
6
5
4
3
2
2
3
4
5
6
7
8
9
10^6
2
3

Figure 6