SLIDE MATERIAL

to the

PAPERMAKING

PROJECT ADVISORY COMMITTEE

March 18 - 19, 1996

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

SLIDE MATERIAL

PAPERMAKING

March 18 - 19, 1996

HEADBOX AND FORMING HYDRODYNAMICS

SLIDE MATERIAL

FOR

PROJECT E00101

March 18 - 19, 1996
Institute of Paper Science and Technology
Atlanta, Georgia

Conservation of Momentum

Vapor

$$\boxed{\frac{\partial}{\partial \tau}\left(\rho_v u_v\right)+\frac{\partial}{\partial z}\left(P_v\right)+\frac{\mu_v u_v}{K}=0} \qquad \textbf{(13)}$$

Liquid

$$\boxed{\frac{\partial}{\partial \tau}\left(\rho_l u_l\right)+\frac{\partial}{\partial z}\left(P_l\right)+\frac{\mu_l u_l}{K}=0} \qquad \textbf{(14)}$$

ORGANIZATION OF THE PRESENTATION

- Project Objectives
- Overall Scope of the Headbox and Forming Program at IPST
- Scope of the Dues-Funded Paper Forming Project
- Tasks for July 1995 to June 1997, and Project Status
- Summary of Recent Results

PROJECT OBJECTIVES

The objectives of this project are to:

(1) investigate and optimize the paper and board forming processes in the wet end of existing machines,

(2) develop novel methods for analysis and control of paper forming, and

(3) develop better designs for paper forming devices

SIGINIFICANT IMPACT ON

PRODUCTIVITY AND QUAILITY

- Hydrodynamic effects in the headbox and the forming section have significant influence on the physical properties and quality of the sheet.
- The maximum speed of the machine and, therefore, productivity is sometimes dependent on the forming section limitations.
- On-line sensors need to be coupled to the forming section operations, therefore, a thorough knowledge of the headbox and forming behavior is needed.

OVERALL SCOPE OF THE PAPER FORMING PROGRAM

- Issues which require fundamental research, understanding, & development (National Science Foundation's Presidential Young Investigator Award)

  Fundamental analysis of: secondary flows due to turbulence anisotropy; turbulent flow in the manifold, tube bank, and converging nozzle; free-surface turbulence jet, flow on the forming wire; turbulence interaction with the fiber suspensions; sedimentation of fiber suspensions and particles on the wire (formation), and innovation of new concepts and devices for more effective paper and board forming.

- Short-term and specific analysis, optimization, and headbox modification (projects with individual companies and organizations)

- Long-term research with short-term generic applications (member companies through Dues-Funded Project)

QUESTIONNAIRE ON HEADBOX AND FORMING HYDRODYNAMICS

Areas of importance	Average rating for Degree of importance (21 companies, 32 responses; 1 - highest priority, 5 - lowest priority)
Fiber orientation nonuniformity in CD	2.0
Basis-weight and/or Caliper nonuniformity in CD	1.44
Moisture variation in CD	1.84
Improve average MD strength	2.67
Improve average CD strength	2.37*
Filler and fines distribution in Z and uniformity in CD	2.58
Wet strength	3.55
Strength uniformity in CD	2.52
Twist/Warp	3.39
Improve formation	2.03
Improve formation uniformity	2.2
Cockle	3.07
Diagonal Curl	3.1
Effect of tube geometry and pattern on formation	3.1
Optimum headbox geometry and design	2.53

Others (please list below)

" Enhance CD strength, CD stiffness, ring crush, STFI, ..."	1
" Headbox hydrodynamics and forming table interaction "	1
" Tools for HB analysis, 2 sidedness, MD variation, surface smoothness "	2

Please outline the most important issue that should be the focus of this project:

- " CD uniformity, formation, strength,..."

SCOPE OF THE DUES-FUNDED PROJECT

- **Based on the Headbox & Paper Forming questionnaire,**

  the issues most important to our member companies are:

  i. **CD nonuniformities in basis-weight (i.e., streaks),**

  ii. **CD nonuniformities in fiber orientation,**

  iii. **Enhance CD strength (stiffness), ring-crush, STFI, ...**

  iv. **Understand and improve formation (fiber dispersion in the headbox and on the forming wire, ...)**

  The long-term issue of importance is:

  v. **Design an optimized headbox and forming section**

APPROACH TO THE DUES-FUNDED PAPER FORMING PROJECT

- Analysis and optimization of headbox hydrodynamics (in-house developed software, generic software, high-speed imaging, and image analysis programs).
- New hydraulic headbox (G1) on the pilot paper machine at IPST for flow visualization and measurements.
- A complete section of a commercial headbox (G2) at the CE Hydraulics lab. for optical diagnostics.
- Optical high-speed visualization and digital image analysis of the paper machine performance at various mills.

TASKS FOR July 1995 to June 1997

1. Fix the IPST paper machine for high-speed flow visualization studies of the flow in the headbox and the jet/wire interaction (complete);

2. Design a generic headbox (G1) for the IPST pilot paper machine (complete);

3. Construct a computational model of the generic headbox (complete);

4. Install a narrow section of a commercial headbox (G2) in the CE Hydraulics Lab for laser doppler velocity and turbulence measurements and to examine new ideas (complete, Laser Doppler Anemometer system is being installed);

5. Fabricate and install the G1 headbox on the IPST machine (Fabrication is complete, installation will be completed by April 96),

TASKS FOR July 1995 to June 1997 (cont'd)

6. Examine the effects of:
   tube diameter and pattern,
   tube shape and length,
   forming jet angle,
   rush/drag and jet/wire interaction, and
   other adjustable features in the forming section

   on small scale (order of 1 inch) basis-weight nonuniformities, fiber orientation nonuniformities, and CD strength properties in the forming section by using computational analysis and the following experimental tools: (in progress)

   a. G1 headbox using dye injection and LDA (starts in April 96);
   b. G2 headbox using Laser Doppler Anemometer (starts in May 96);
   c. G1 headbox using computational and image analysis (in progress);

7. Using a pilot machine, examine the effects of adjustable parameters to the headbox on small scale (order of 1 inch) basis-weight nonuniformities, fiber orientation nonuniformities, and CD strength properties of the sheet (have identified one pilot facility suitable for this work, this work starts ~ Fall 96);

8. Analyze the effects of turbulent flow in the head box and the forming section on fiber & filler dispersion/flocculation/distribution and, subsequently, on Paper formation (in progress);

TIME TABLE FOR THE TASKS PROPOSED FOR 1995-1997 (starting from July 1995):

```
                         March 1996
                              |
                              |
Months:   1     3     6     |9    12    15    18    21     24
                              |
Tasks                         |

1       +------+ (complete)
2          +-----+ (complete)
3          +-----------------+ (complete)
4             +-------+ (complete)
5                +---------+
6a                        +---------------------------+
6b                         +----------------------------+
6c                      +--------------------------------+
7                                    +-------------------
8             +--------------------------------------------
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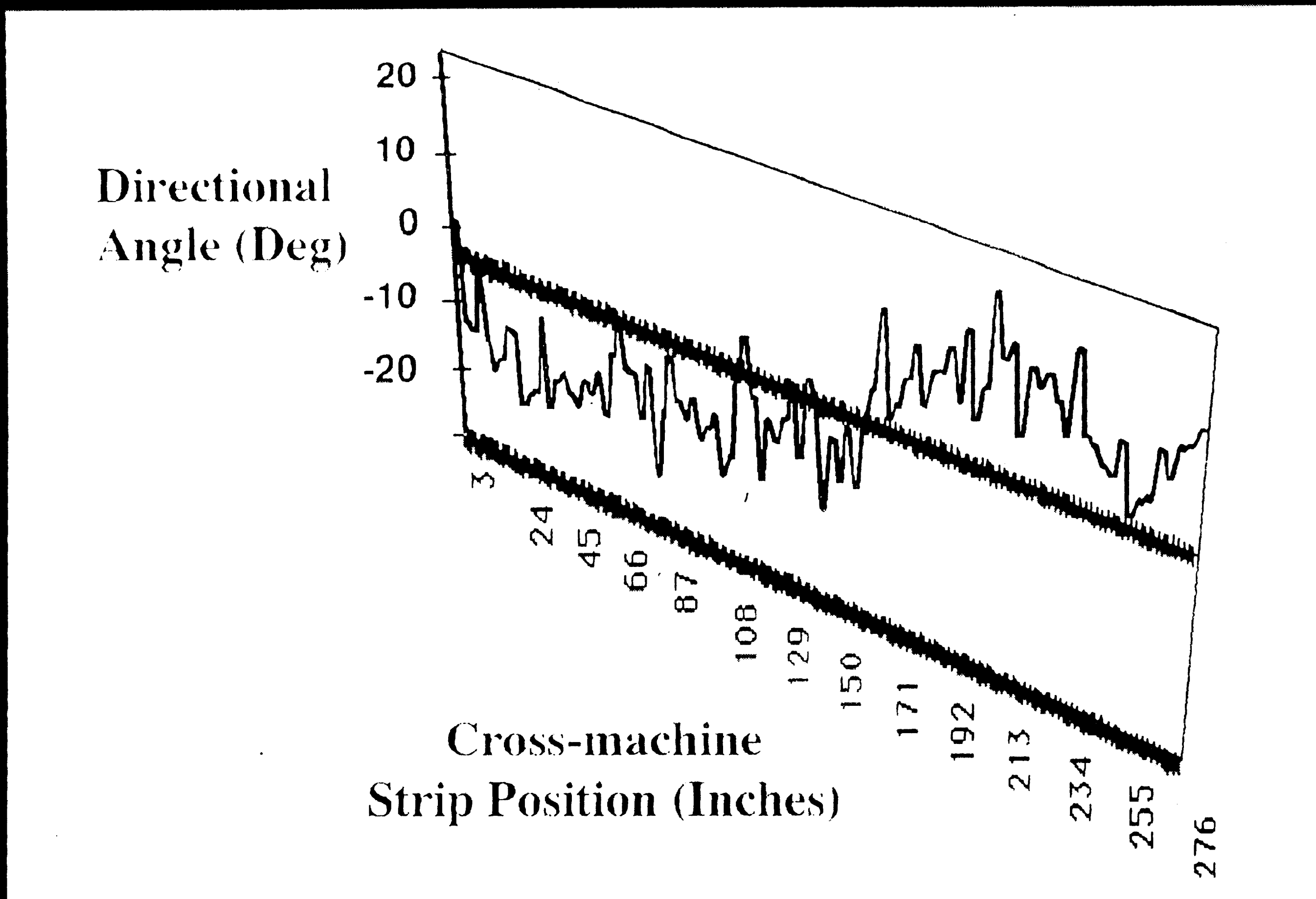
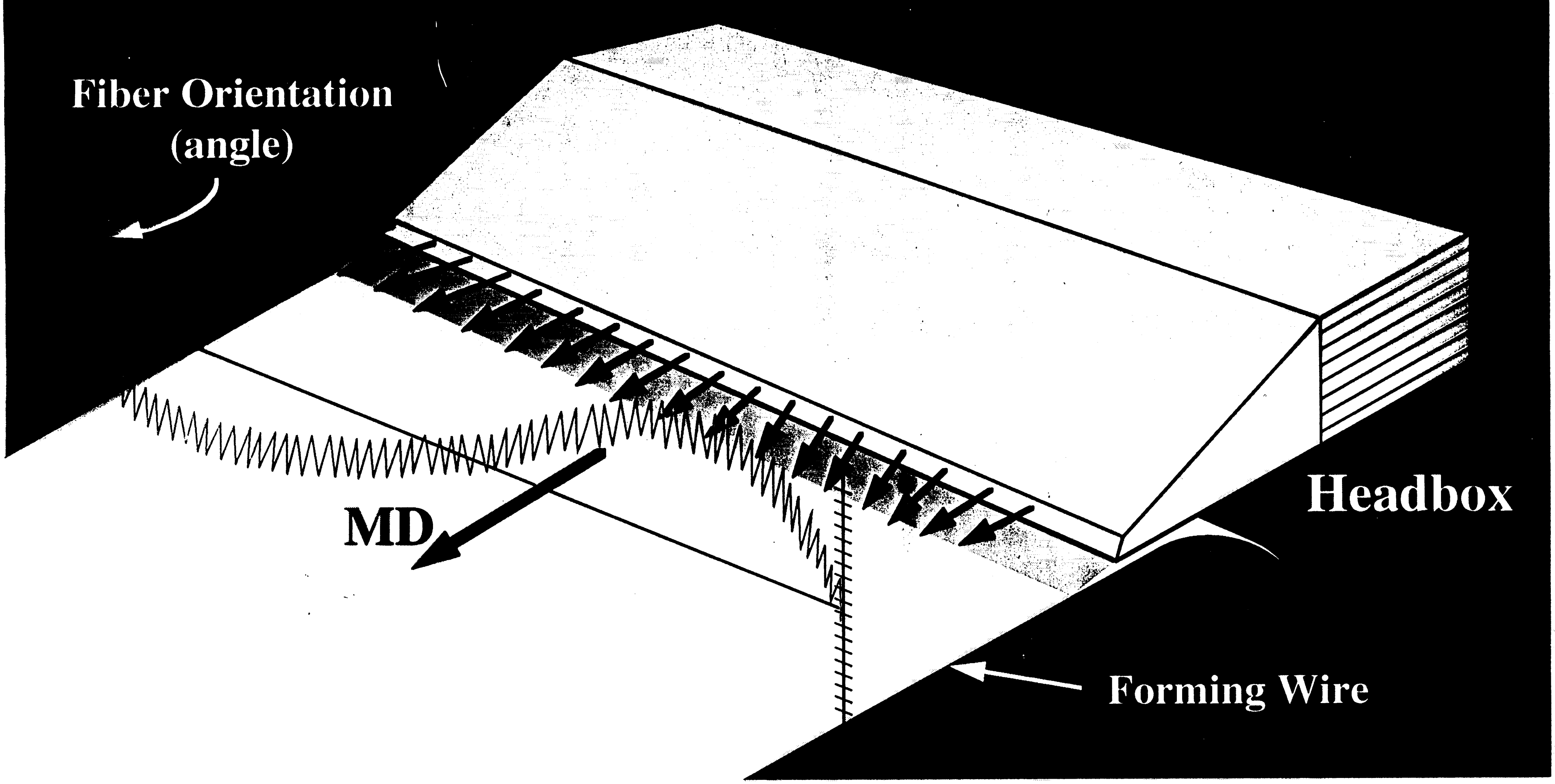
PREVIOUS WORK AND BACKGROUND INFORMATION

Fiber-orientation Nonuniformity in the Cross-machine Direction

Fiber Angle Profile Across the Machine

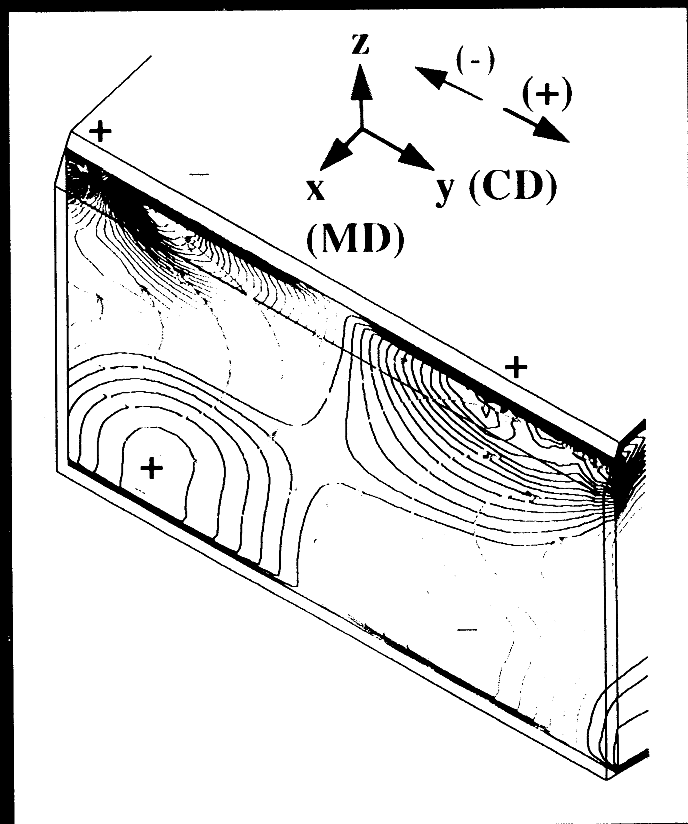


Fiber Orientation Nonuniformity Due to Secondary Flows in the Headbox and Nonuniform Jet Alignment with the Wire

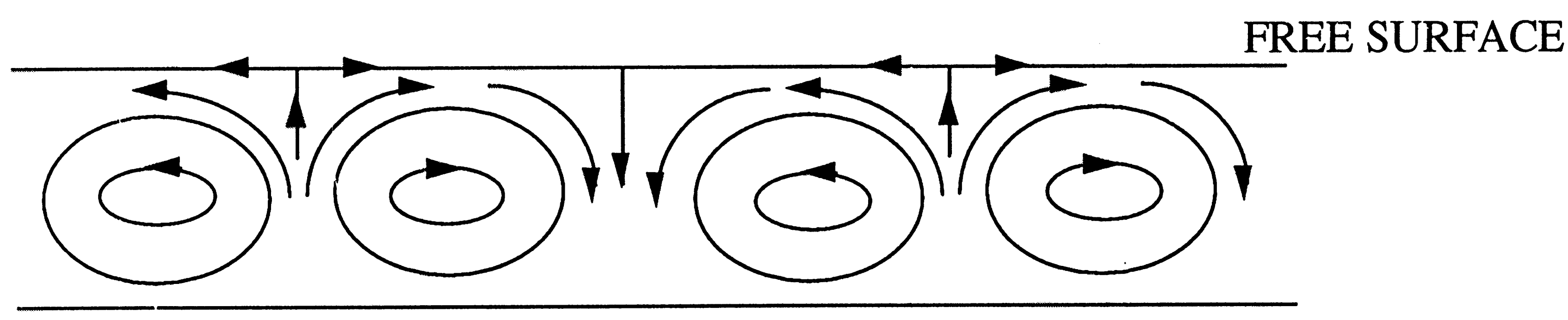


Basis-weight Nonuniformity in the Cross-machine Direction

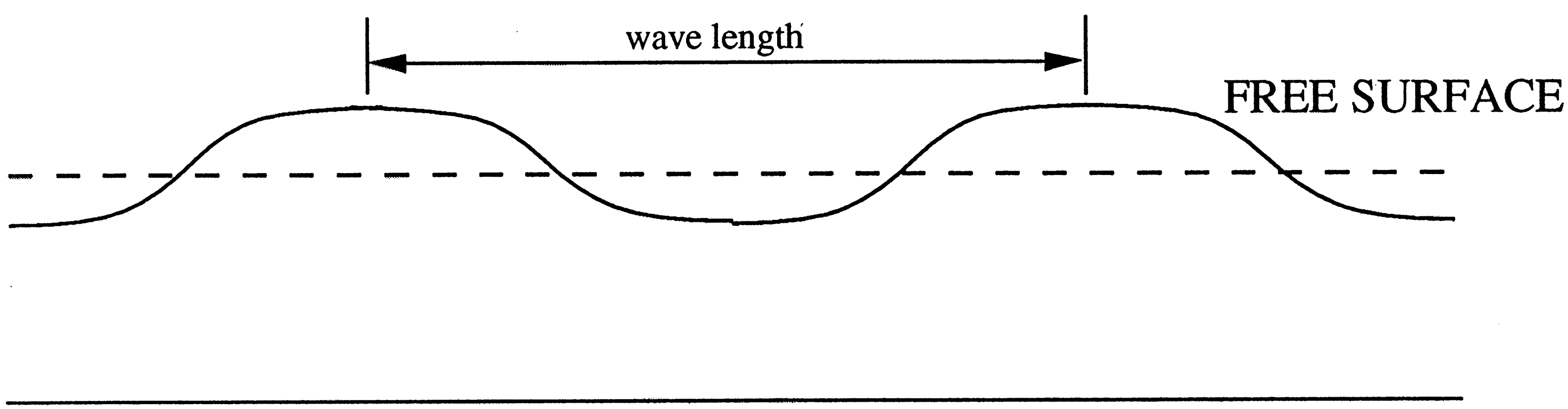
Contour Plot of the CD Velocity Component at the Slice (nonuniform flow rate through the tubes)



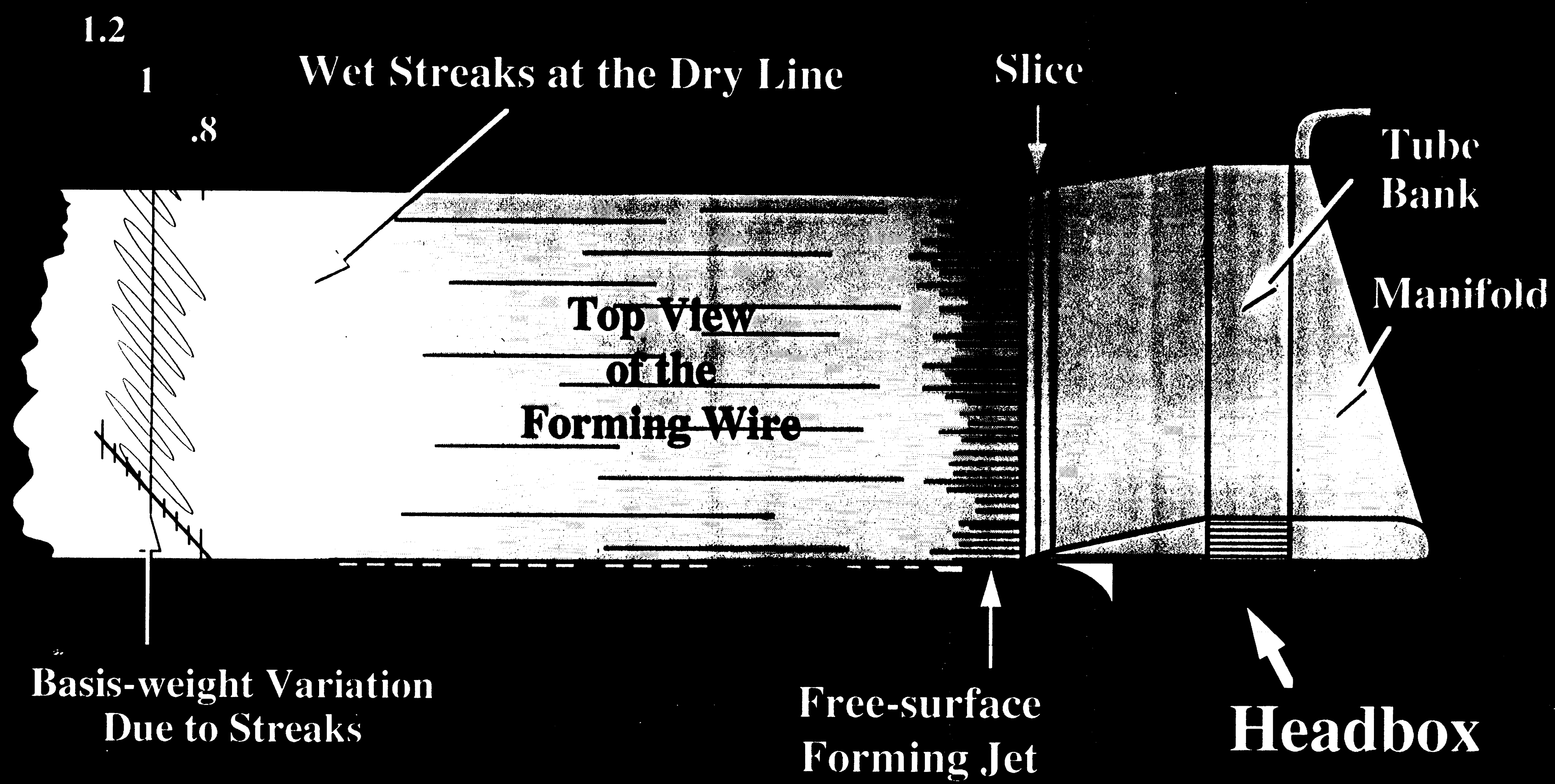
PERIODIC SECONDARY FLOWS GENERATE → WAVES (STREAKS)



Kinetic Energy - Dissipation = Potential Energy



Streaks on the Fourdrinier Table Resulting in Basis-weight Nonuniformity



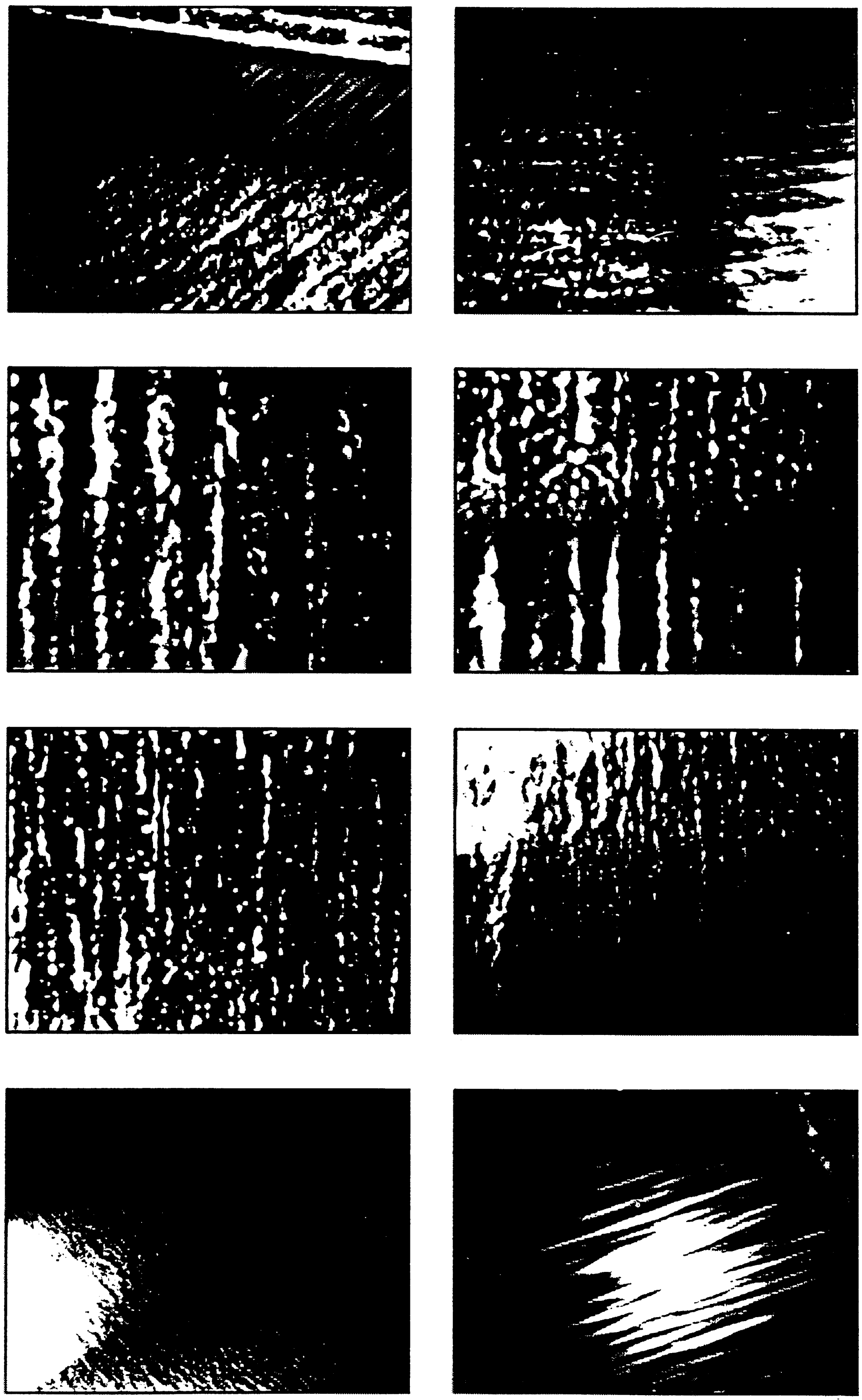
SUMMARY OF RECENT RESULTS

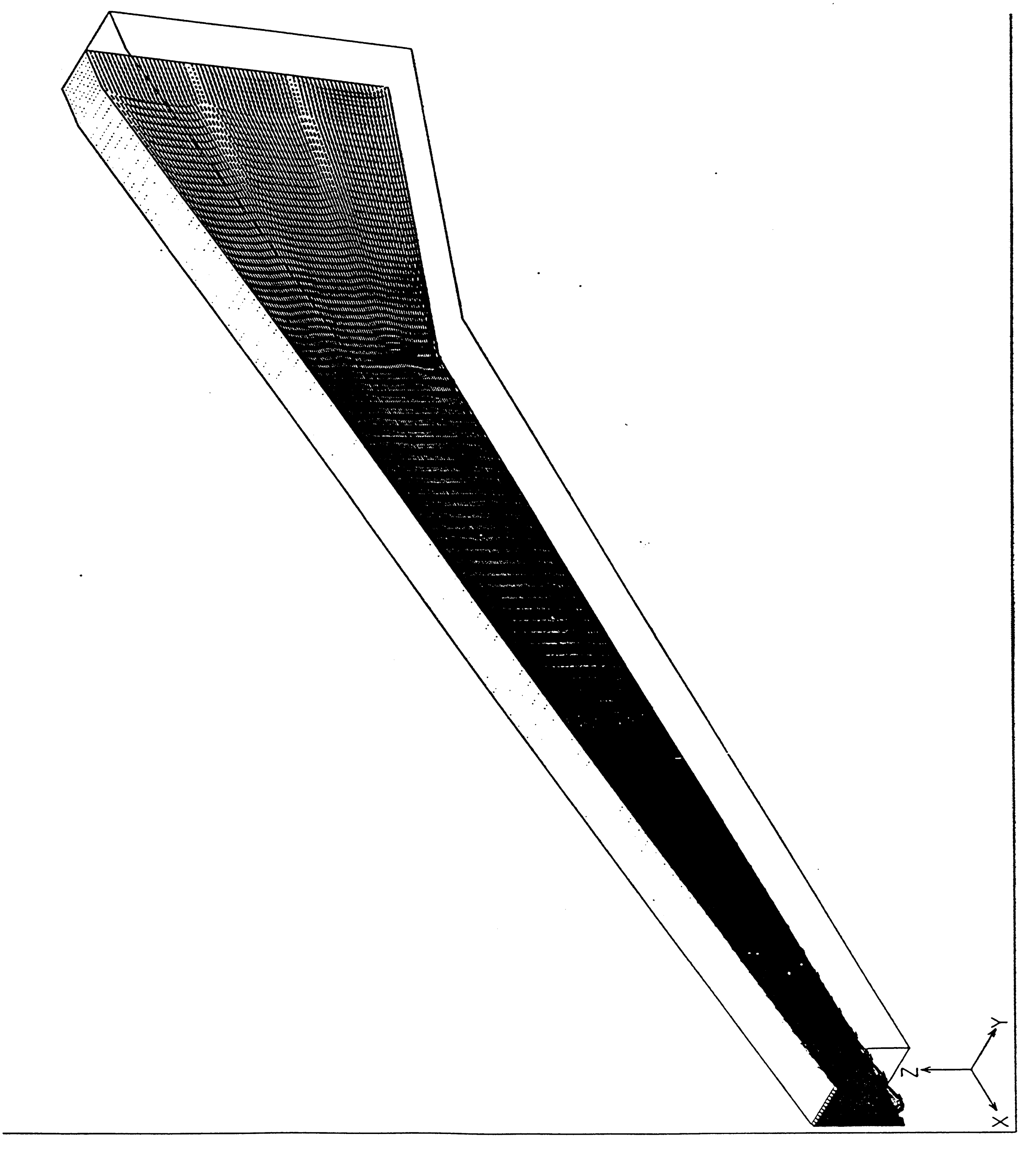
1. High-speed imaging and digital image analysis has been applied as a diagnostics method for characterization of streaks and small-scale basis-weight variations.

2. Computational analysis of the G1 headbox shows the dynamic character of secondary flows due to jet/jet interaction in the converging section (video presentation).

3. The effect of mean flow in the tubes on the turbulent kinetic energy, turbulent eddy viscosity and turbulent eddy scale at the slice have been computed. The effects on formation characteristics will be discussed.

Sample pictures of the forming section from the high-speed imaging work. The image quality deteriorates when reproduced with regular copy machines. Better quality images will be presented at the meeting.




Y
Z
X

THE EFFECT OF TURBULENT FIELD ON DESTRUCTION OF FIBER FLOCS

$$\Delta t = F\left(\frac{1}{\mu_t \|\varepsilon\|}, \tau_o, \alpha\right)$$

Δt	**is the time it takes for the size of a floc of fiber to be reduce by 90% in a turbulent field.**
$\|\varepsilon\|$	**magnitude of shear strain**
τ_o	**type of yield stress (force/area) - the minimum stress required to disrupt the flocs**
α	**constant which depends on the type of fiber and the floc network characteristics.**
μ_t	**turbulent viscosity** ($\mu_t\|\varepsilon\|$ **is a measure of turbulent stress**)

Figure 1.

Turbulent Kinetic Energy Distribution at the Outlet

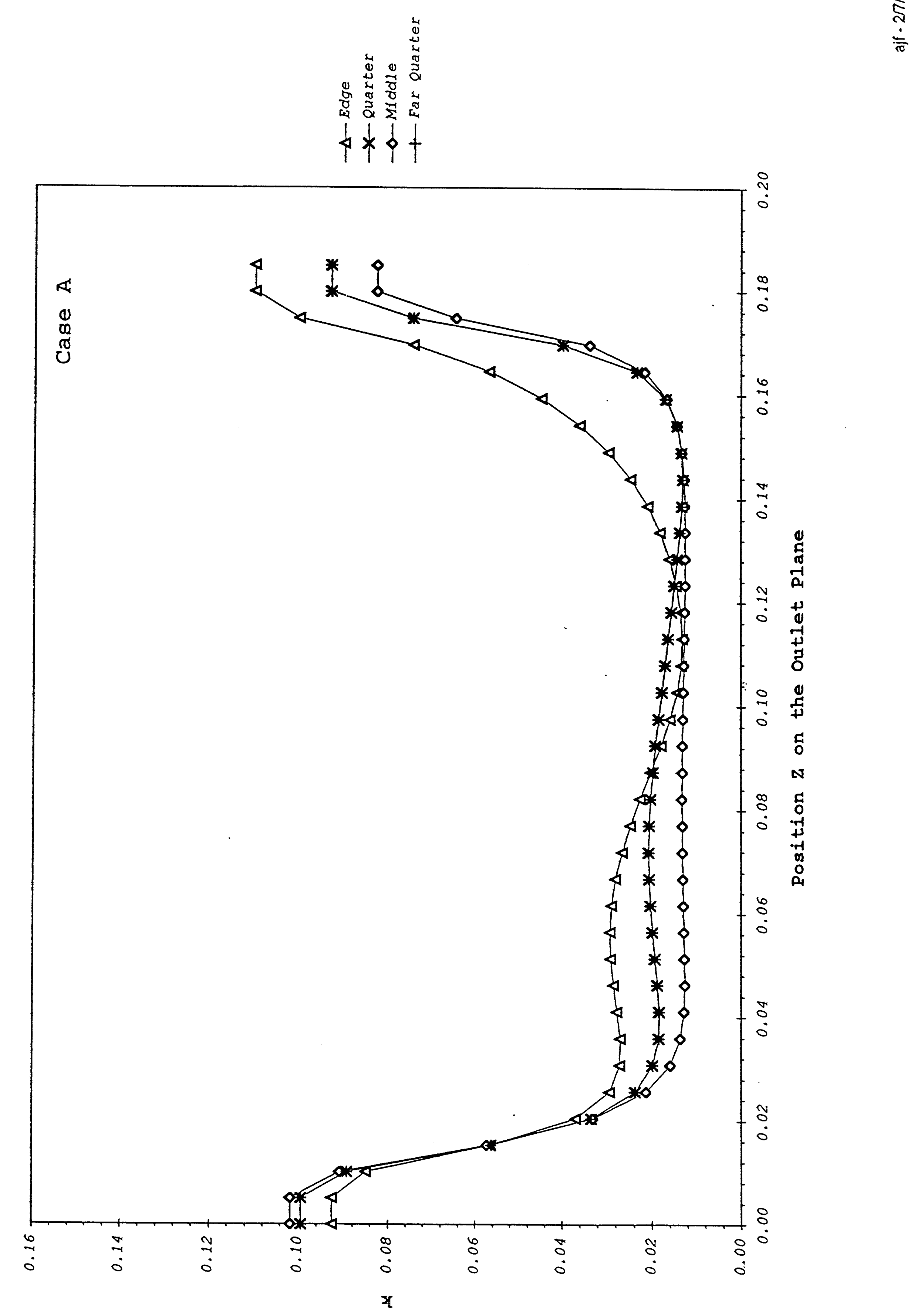
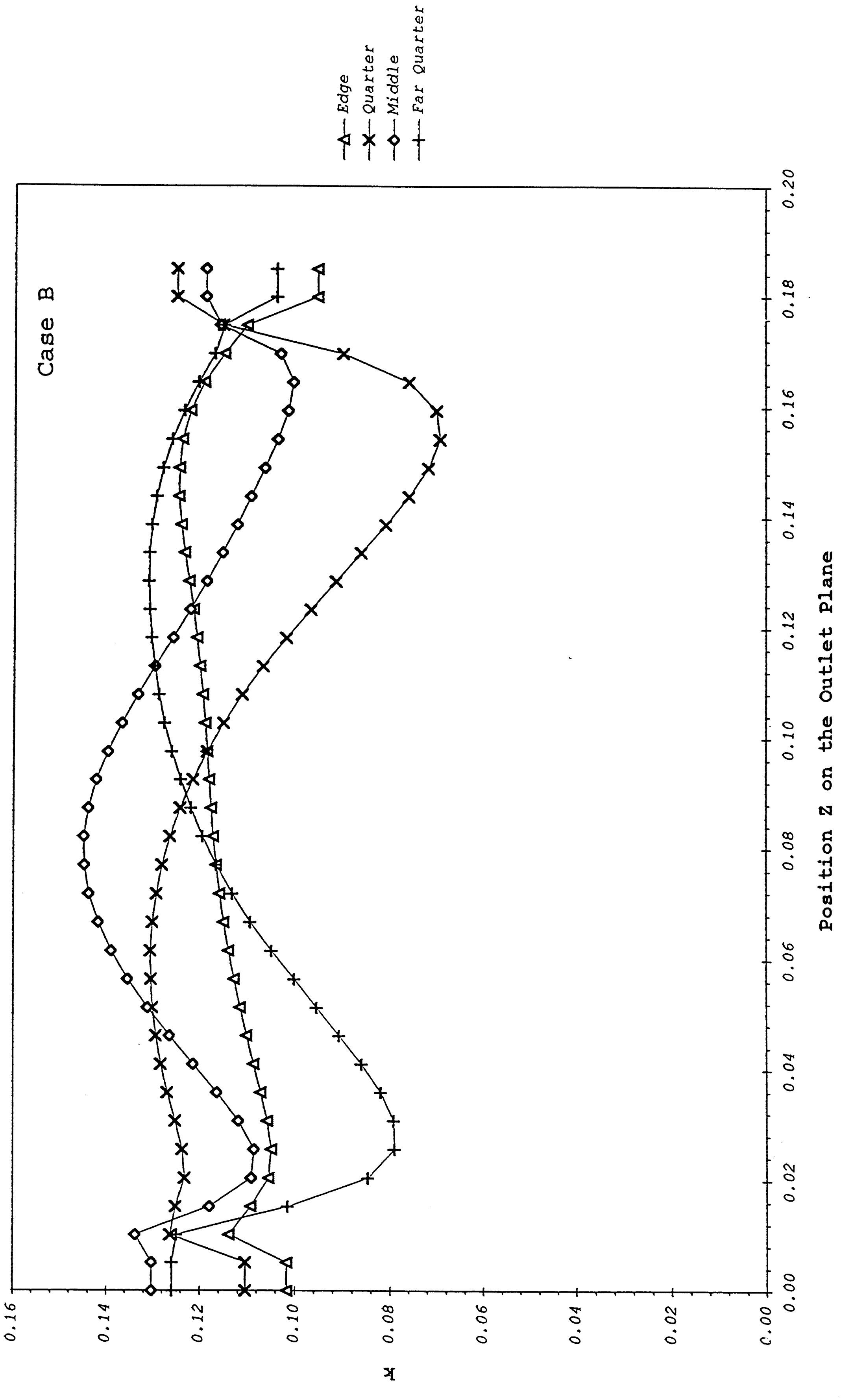


Figure 2.

Turbulent Kinetic Energy Distribution at the Outlet



ajf - 2/7/96

aj' - 2/7/96

Figure 3.

Turbulent Eddy Viscosity Distribution at the Outlet

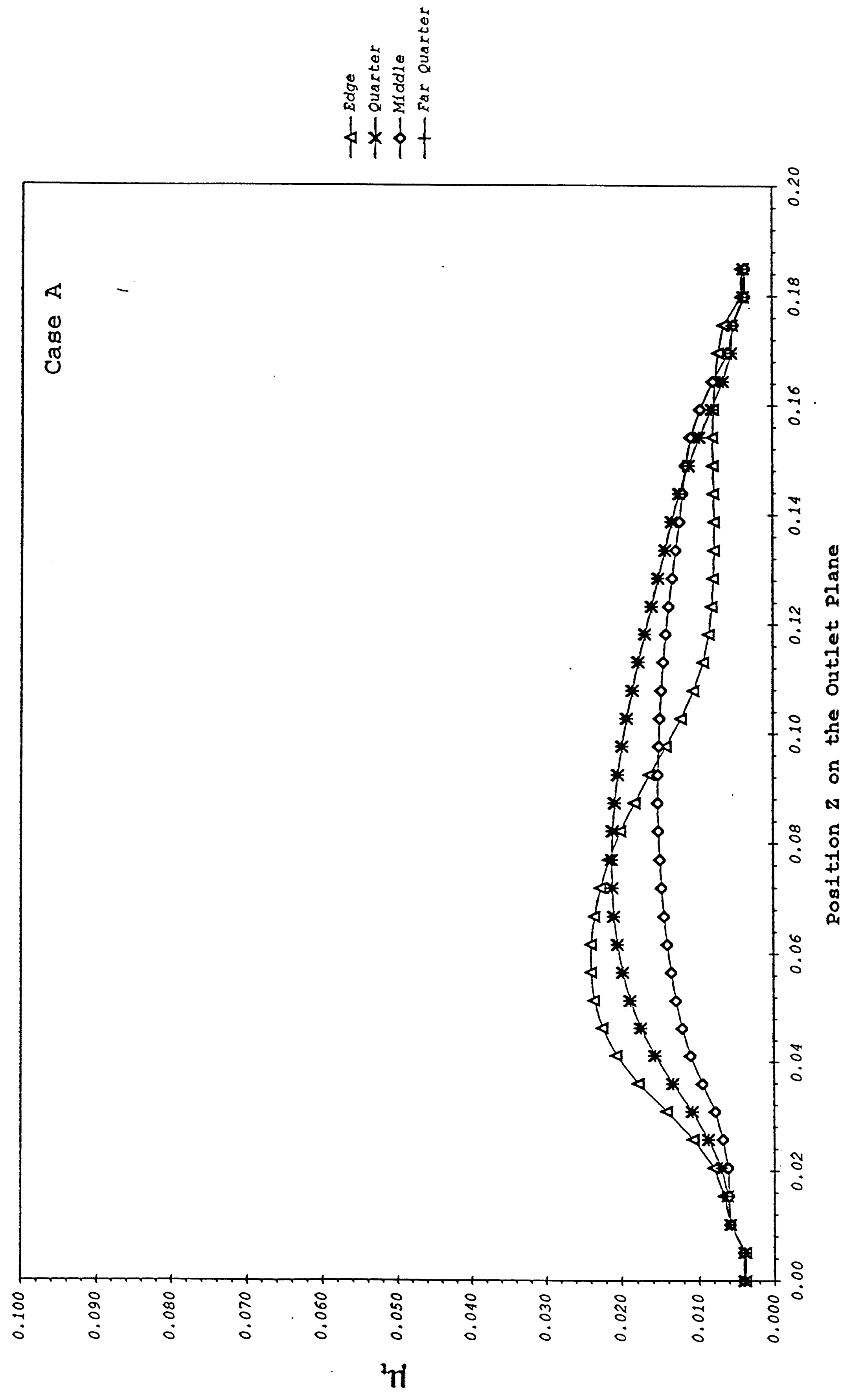
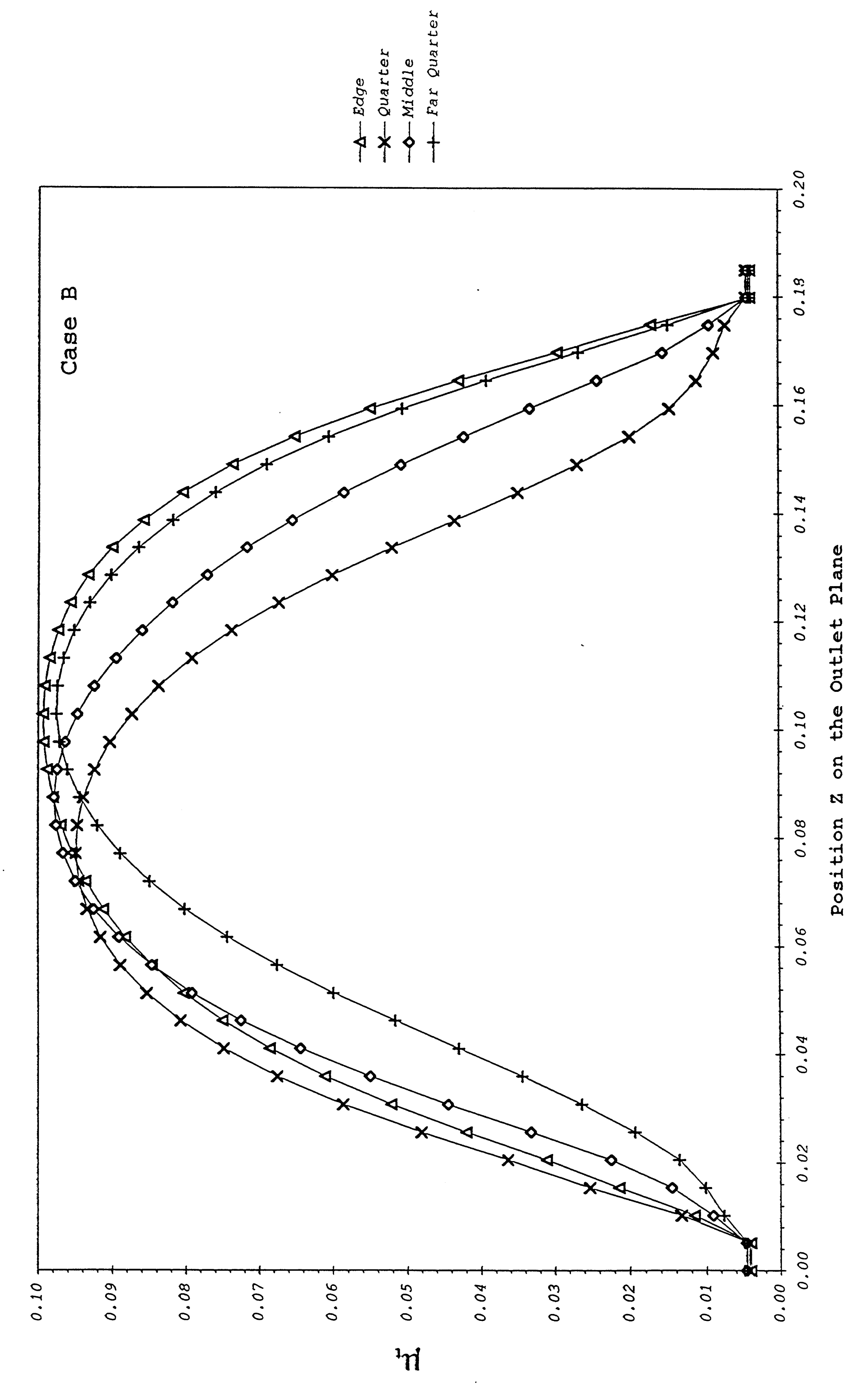


Figure 4.

Turbulent Eddy Viscosity Distribution at the Outlet



ajf - 2/7/96

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Figure 5.

Eddy Characteristic Size Distribution at the Outlet

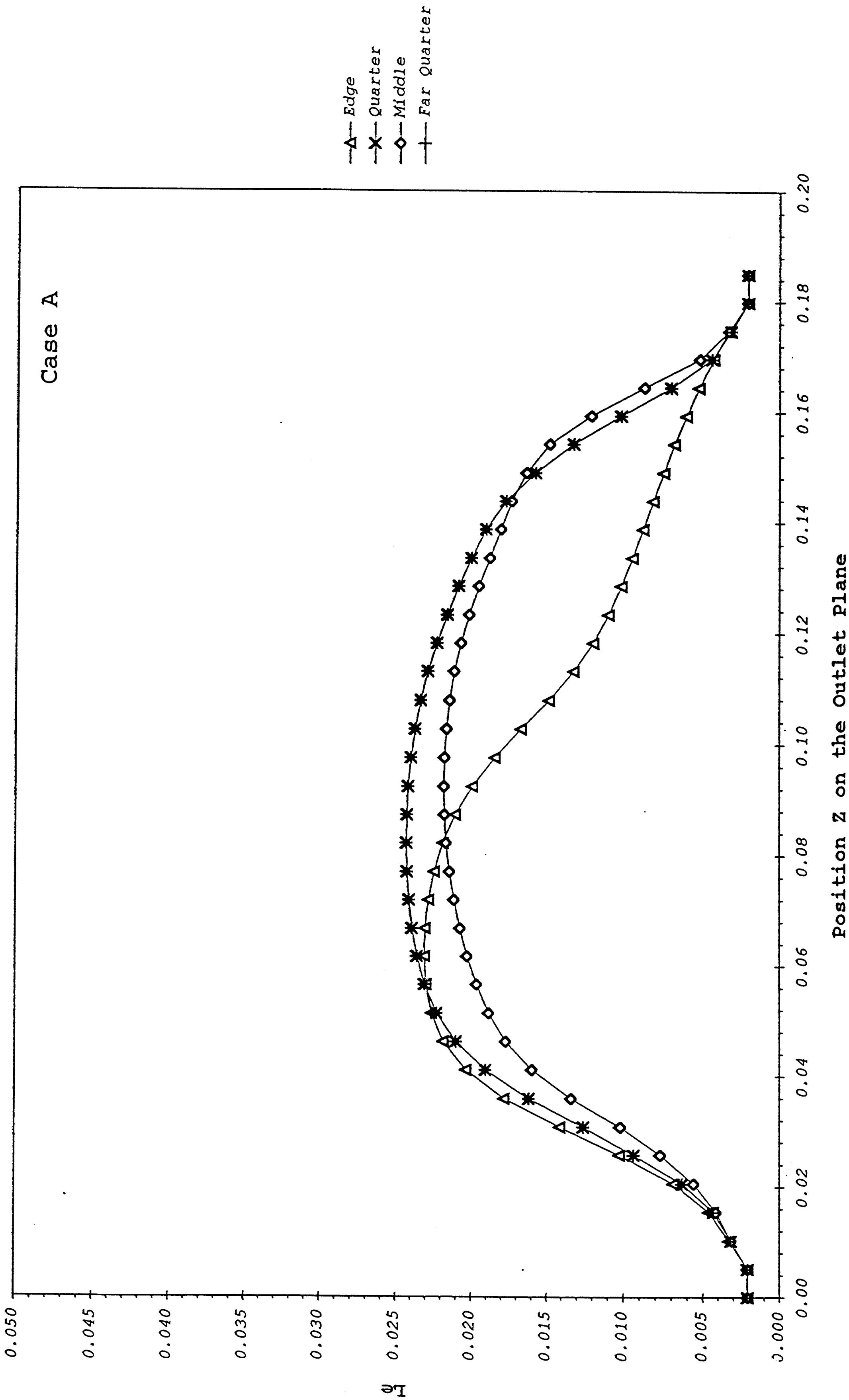
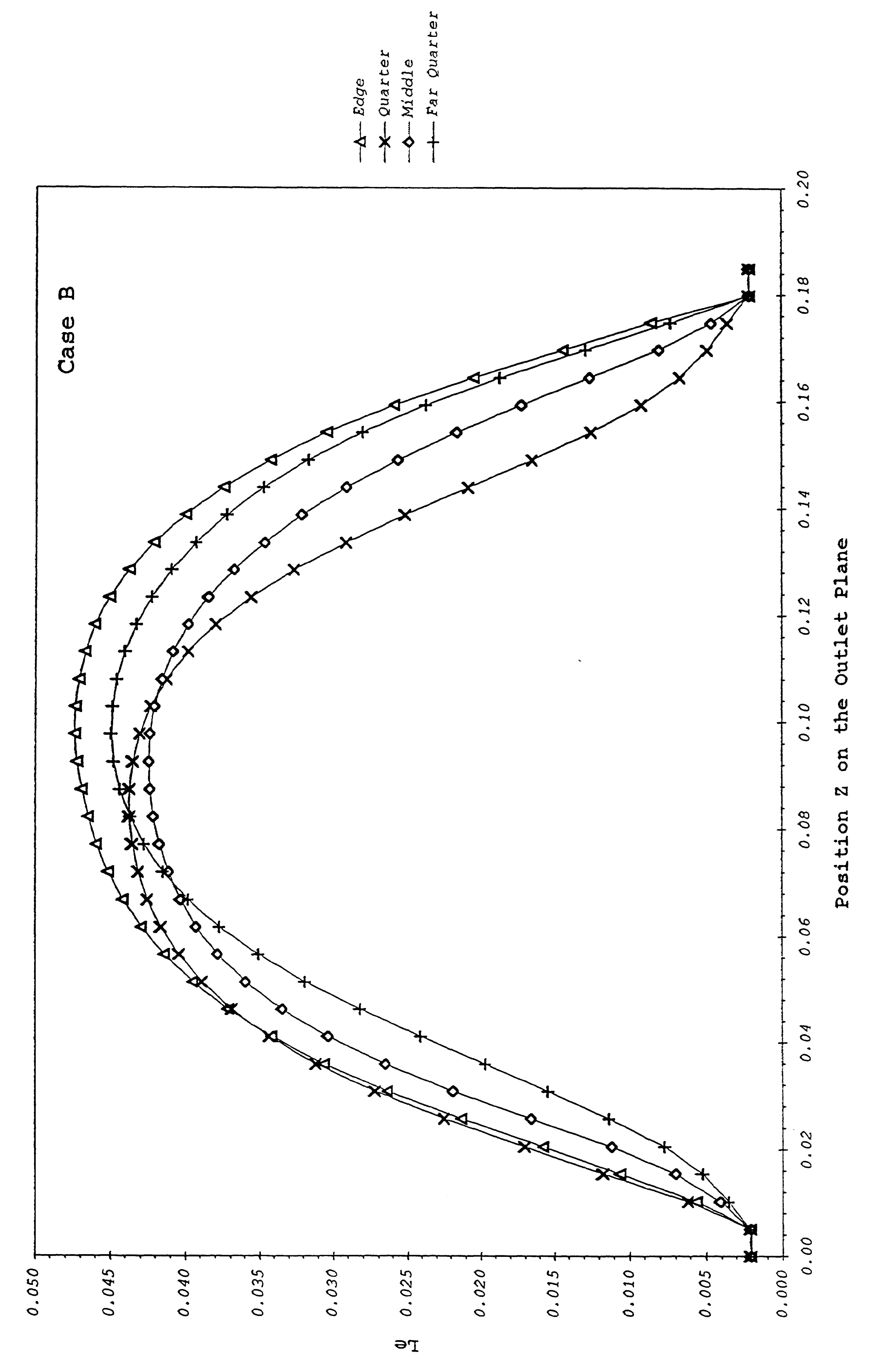


Figure 6.

Eddy Characteristic Size Distribution at the Outlet



ajf - 2/7/96

CONCLUSIONS AND RECOMMENDATIONS FOR IMMEDIATE IMPLEMENTATION

CD BASIS WEIGHT NONUNIFORMITY:

BW nonuniformities >4 inches may be due to:

1. **Structural defects in the headbox, slice opening nonuniformities such as bent lip, tube plugging and/or wear, nonuniformity in consistency, jet level misalignment, nonuniformities and wear in the drainage elements, . . . (usually engineers at the mill should be able to detect these problems)**

2. **Relatively long stable streaks at the dry line (call IPST)**

BW nonuniformities between 0.5 to 4 inches or ridges that exist across the machine may be due to:

Jet/jet interaction in the converging zone, streaks in the forming jet and amplification upon impact on the forming table, streaks on the table, accumulated effect of the nonuniformities on the forming table, . . . (call or send samples to IPST)

CONCLUSIONS AND RECOMMENDATIONS FOR IMMEDIATE IMPLEMENTATION (cont'd)

CD IN-PLANE FIBER ORIENTATION NONUNIFORMITY:

Large scale (in the order of machine width) CD nonuniformity may be due to:

> **Secondary flows of the first kind from edge effects. Usually can be fixed with hydraulic headboxes. This nonuniformity increases when decreasing rush/drag (call and send CD strip samples to IPST)**

> **Pressure not balanced in the manifold, nonuniform slice opening, side flow ejection/injection, . . . (engineers at the mill can usually address these issues)**

Small scale (in the order of 2 to 20 inches) CD nonuniformities may be due to:

> **Jet/wire interaction, small scale secondary flows in the headbox, . . . (call and send samples to IPST)**

IN-PLANE FIBER ORIENTATION NONUNIFORMITY IN THE ZD:

> **Mean velocity gradient in the forming jet and nonuniform shear in the forming section, . . . (call IPST)**

FUNDAMENTALS OF WEB HEATING

SLIDE MATERIAL

FOR

PROJECT F002

March 18 - 19, 1996
Institute of Paper Science and Technology
Atlanta, Georgia

F002: Fundamentals of Web Preheating

PI: Timothy F. Patterson, David I. Orloff

Key Personnel: Paul Phelan, Isaak Rudman

Institute of Paper Science andTechnology

Outline

I. Program Objectives

II. Survey Results

III. Summary of Work to Date

IV. Proposed Investigations

V. Preliminary Results

Program Objectives

I. Web Preheating

Comprehensive model of web preheating

What is the optimum way to heat the web?

II. Hot Pressing

Predictive model of water removal and sheet property changes due to incremental increases in web temperature

What are the resultant production and strength increases ?

Survey

What applications of steamboxes are of the greatest interest to you?

1. **Heating for increased productivity** — **High**
   F002 Ojective I

2. **Heating for profile control** — **Medium**
   F002 Ojective I

3. **Heating for quality enhancement** — **Medium**
   F002 Ojective II

Results: October 1995 - March 1996

1. **Determine correlation between specific surface and steam heating**

    - Water Permeability Method Developed.

2. **Determine correlation between specific surface, ingoing sheet temperature and outgoing pressed sheet properties**

    - Water Permeability Method Developed.

Results: October 1995 - March 1996

3. Investigate heat and mass transfer models for web steam preheating
   - model identified and formulated.

4. Identify factors influencing vacuum box effectiveness
   - Master's Thesis (J. C. DeBraal).

5. Determine importance of boundary layer in steam heating
   - postponed until fall '96.

Overall Plan

Experimental

1. Use Steambox Comparator to
   steam preheating - OCC, Virgin Kraft
2. Use MTS Hydraulic Press to
   hot pressing - OCC, Virgin Kraft

Theoretical

1. comprehensive steaming model
2. predictive pressing model

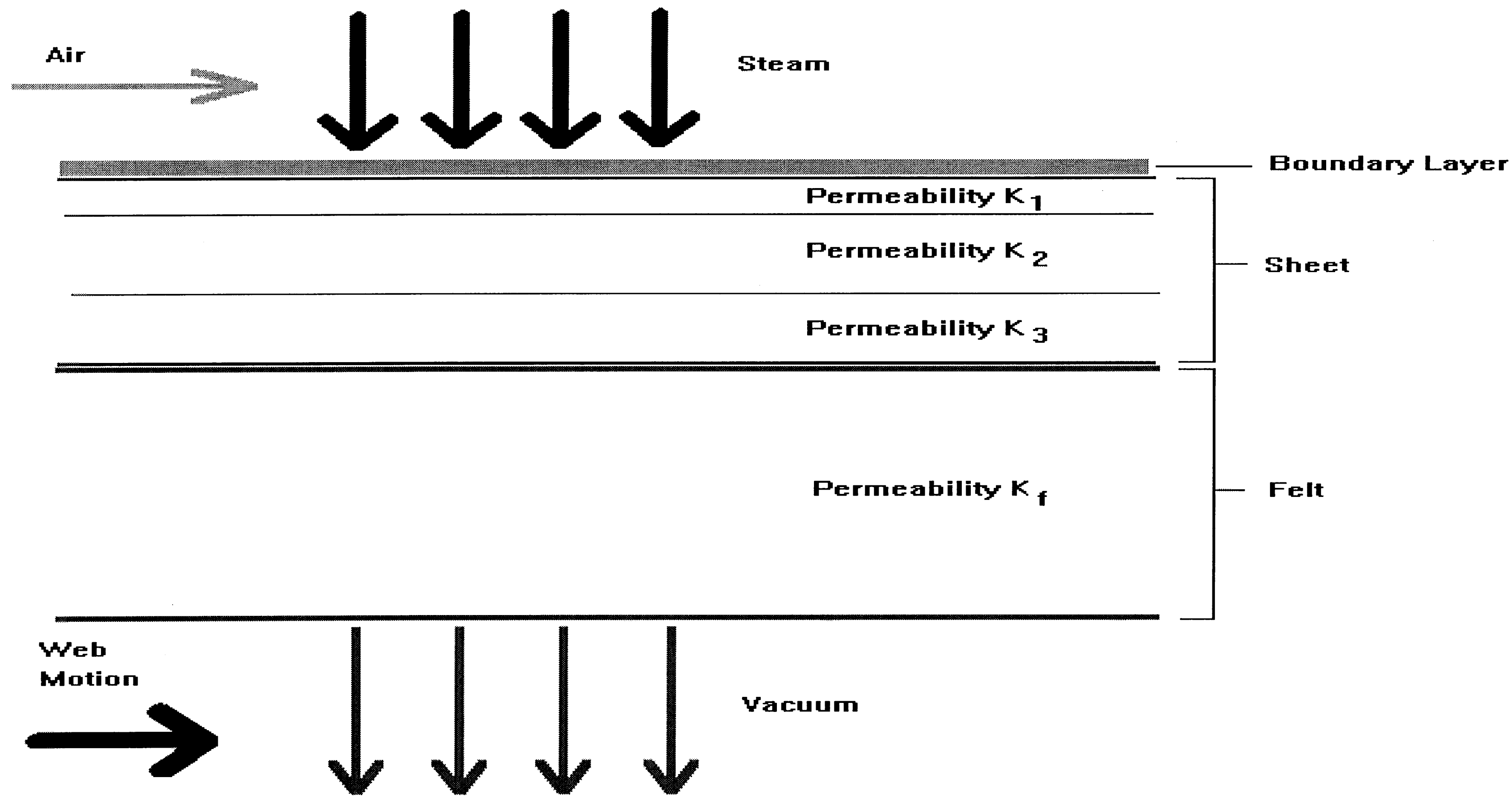
Web Preheating: March 1996 --->

1. Complete Master's Thesis. . . . . . . may '96
2. Model Programming . . . . spring/ summer '96
3. Steambox Comparator (OCC). . . .spring '96
4. Steambox Comparator . . . . .fall '96 (Virgin Kraft)
5. Thermal Diffusivity and. . . . . summer/ Convective Heat Transfer fall '96

Hot Pressing: March 1996 --->

1. Pressing Test Plan. . . . . complete
2. OCC Pressing . . . . spring '96
3. Predictive Model Investigation. . . summer /fall '96
4. Virgin Kraft Pressing. . . . . fall '96

Preheating Model



Steam Energy = ***f*****(temperature, pressure, mass flow rate, velocity, dwell time)**

Boundary layer = ***f*****(speed, sheet surface, steam box geometry)**

Air = ***f*****(speed steambox geometry)**

Sheet Permeability = ***f*****(furnish, solids, temperature, basis weight)**

Felt Permeability = f(construction, material, moisture, dirt)

Vacuum = ***f*****(slot width, slot spacing, dwell time, vacuum level, air flow rate)**

Model Elements

1. Processes occurring inside the sheet
2. Steam jet impingement on the sheet surface
3. Vacuum application
4. Conduction and convection processes after exiting the steambox

Conservation of Mass

Liquid

$$\boxed{\frac{\partial}{\partial \tau}\left(\varepsilon_l \rho_l\right)+\frac{\partial}{\partial z}\left(\rho_l u_l\right)=\dot{m}_{vl}} \qquad (5)$$

Vapor

$$\boxed{\frac{\partial}{\partial \tau}\left(\varepsilon_v \rho_v\right)+\frac{\partial}{\partial z}\left(\rho_v u_v\right)=-\dot{m}_{vl}} \qquad (7)$$

Conservation of Energy

Liquid - Solid

$$\left(\varepsilon_s \rho_s c_{ps} + \varepsilon_l \rho_l c_{pl}\right)\frac{\partial T}{\partial \tau} = \left(\varepsilon_s k_s + \varepsilon_l k_l\right)\frac{\partial^2 T}{\partial z^2} + h a_s \left(T_v - T_s\right) + \Delta h_{vap} \dot{m}_{vl} \quad (10)$$

Vapor

$$\left(\varepsilon_c \rho_v c_{pv}\right)\frac{\partial T_v}{\partial \tau} + \left(\rho_v c_{pv} u_v\right)\frac{\partial T_v}{\partial z} = -h a_s \left(T_v - T_s\right) \quad (11)$$

HEADBOX AND PAPER FORMING ANALYSIS AND OPTIMIZATION (E00101N)

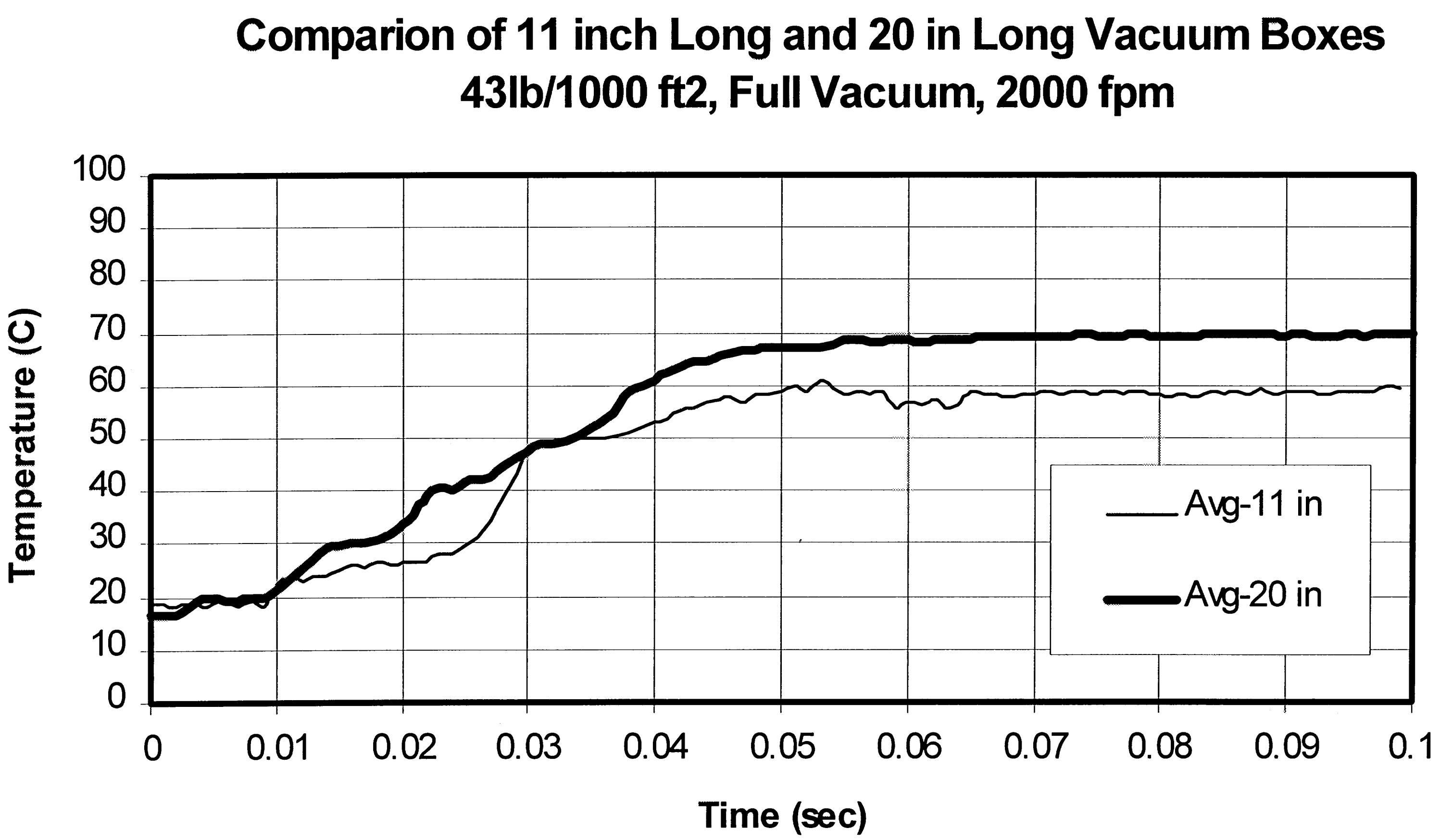
REPORT TO THE

PAPER MAKING PROJECT ADVISORY COMMITTEE

TEAM: Cyrus Aidun, Principal Investigator
Adrian Ferrier, Assistant Engineer

Spring 1996

MS Thesis - Vacuum Box Length Weighted Average Temperature



Specific Surface - Effect of Air

Specific Surface - OCC Measurements

FUNDAMENTALS OF DRYING

SLIDE MATERIAL

FOR

PROJECT F001

March 18 - 19, 1996
Institute of Paper Science and Technology
Atlanta, Georgia

Fundamentals of Drying: Impulse Drying

David Orloff

Impulse Drying

- F001: Fundamental Research - IPST Dues Funded
- 3595: Pilot Scale R & D - IPST/Beloit DOE / Beloit Funded

Objectives

- Fundamental Research -

  Expand impulse drying operating window to a wider range of grades and funishes.

- Pilot Scale R & D -

  Develop impulse drying of board grades and demonstrate on a pilot papermachine.

F001 Accomplishments

- Discovered that opening nip to high "ambient" pressures eliminates sheet delamination. U.S. patent filed 5/95.
- Discovered that delamination can also be suppressed by modifying the nip decompression rate during nip opening. U.S. patent in preparation.

F001 Accomplishments

- Developed thermodynamic model of evaporation during nip opening.
- Theory was used to identify mechanisms involved in the modified nip decompression experiments.

3595 Accomplishments:

- Negotiated agreements with Beloit on commercialization of IPST impulse drying technology for board grades.
- Obtained DOE funding and Beloit involvement and contributions for a two-year continuous high-speed pilot impulse drying development and evaluation project.

3595 Accomplishments:

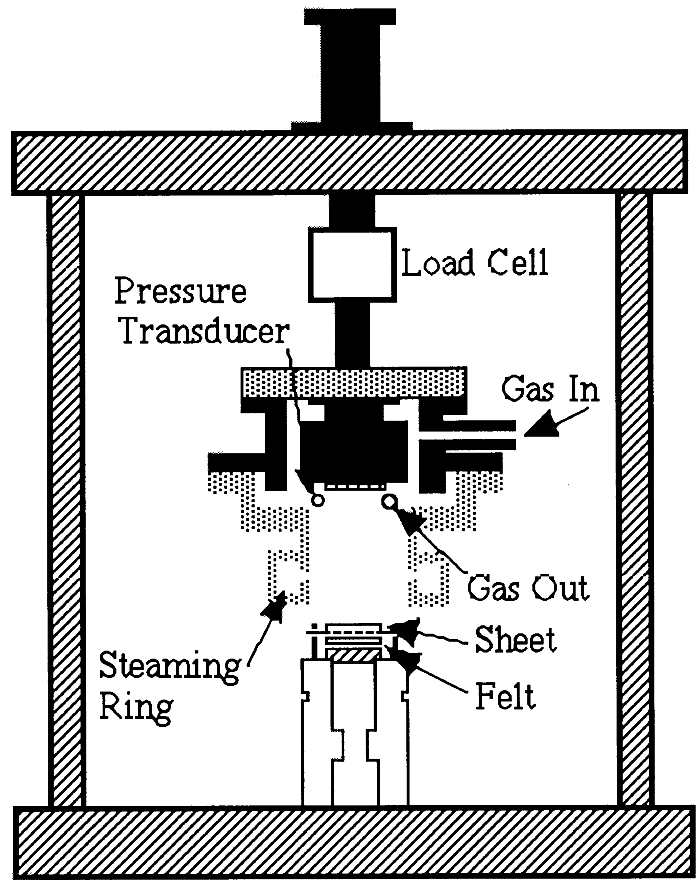
- IPST is preparing four roll coatings for evaluation on the IPST impulse drying durability test facility.

Outline Of Results

- High ambient pressure impulse drying (HAPID) experiments.
- Ramp decompression experiments.
- Theoretical model and implications.

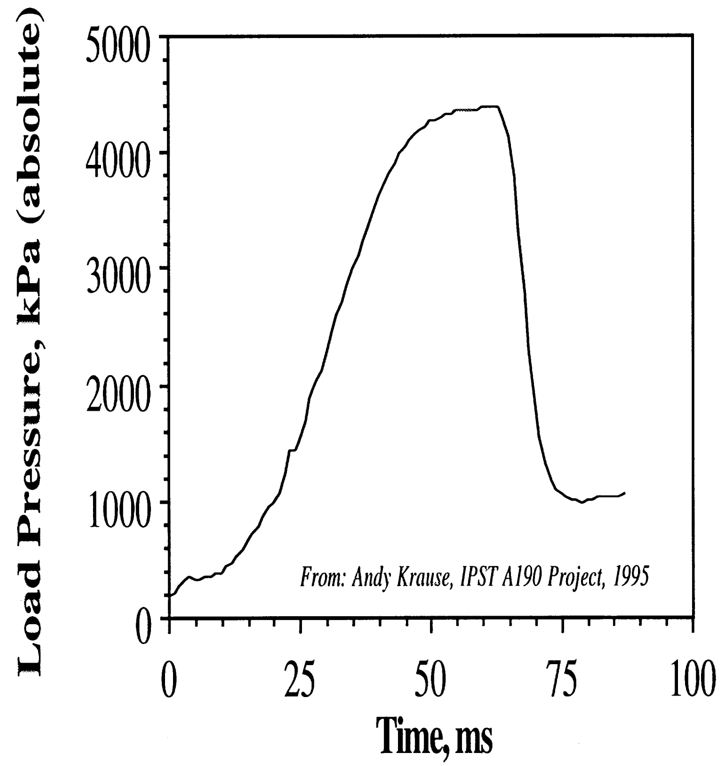
HAPID Simulator

- Impulse dryer built into a pressure chamber.
- Simulates opening nip to high ambient pressure.
- 42#liner at 400 ml. CSF at 35% Sin Evaluated.



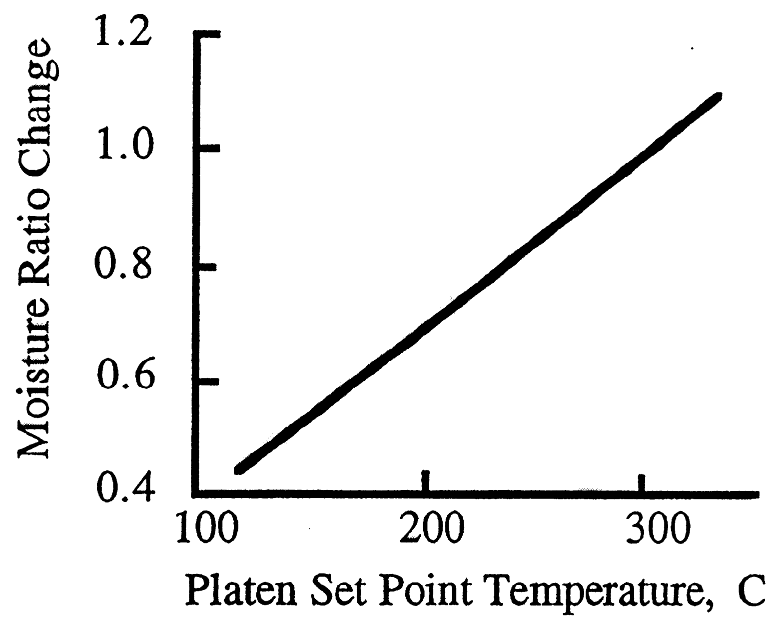
HAPID Pressure Pulse

- Gas added to chamber at mid-nip.
- Ambient pressure at nip opening can be controlled.
- Delamination suppressed at critical ambient pressure.



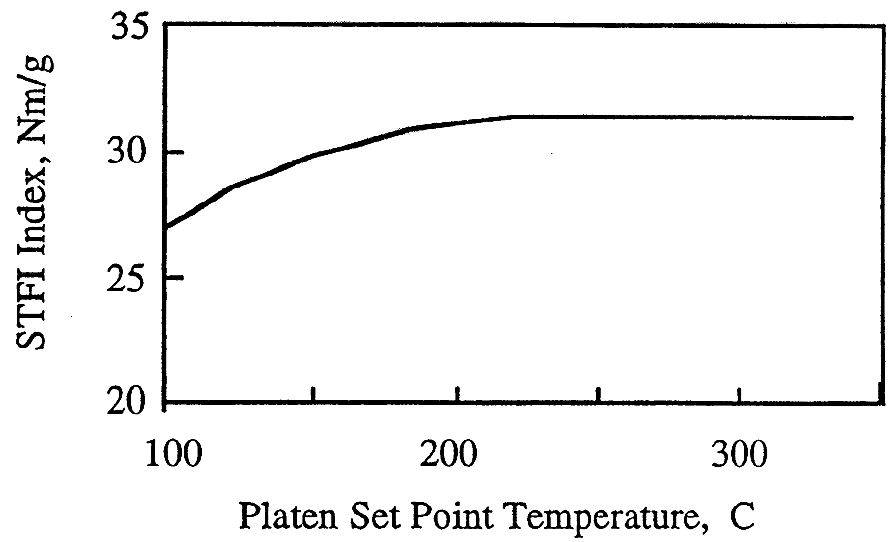
HAPID Water Removal Data

- Water removal was proportional to platen temperature,
- And independent of ambient pressure at nip opening.



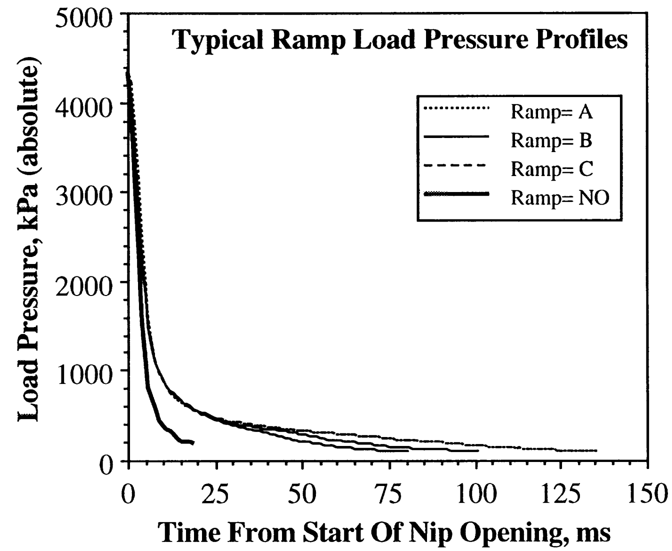
HAPID Sheet Strength

- STFI Compression strrength increased with platen temperature.
- Limit seems to have been reached.

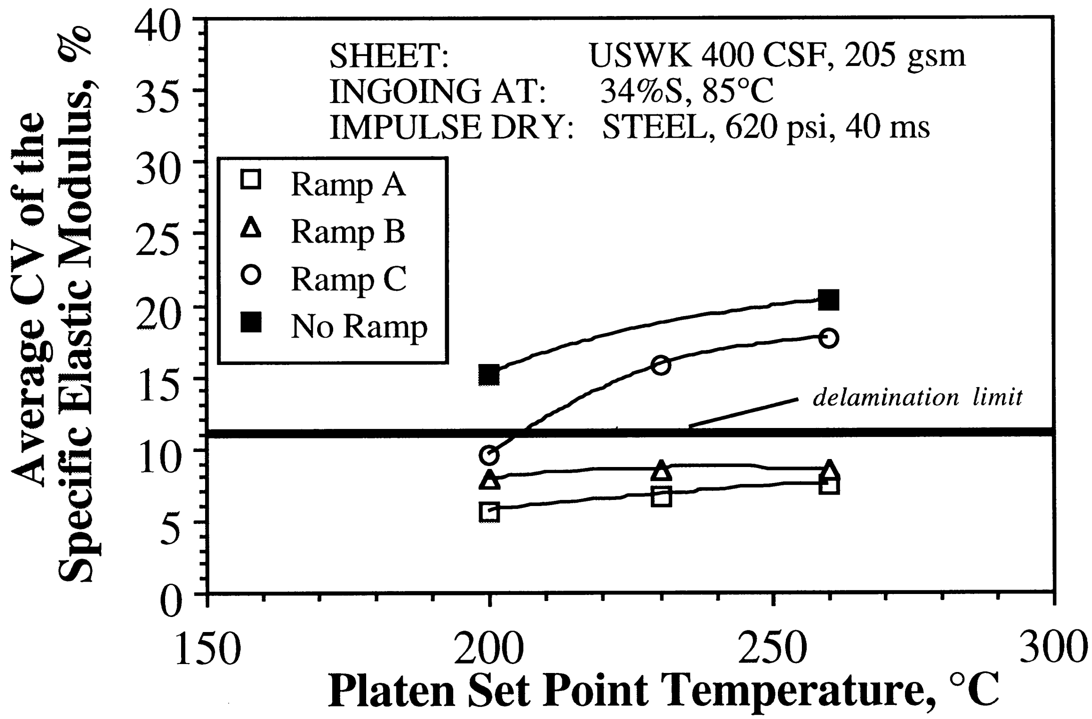


RAMP decompression Experiments

- Nip opening decompression rate was varried.
- 42# liner at 400 ml. CSF at 35% Sin evaluated.



RAMP decompression Experiments

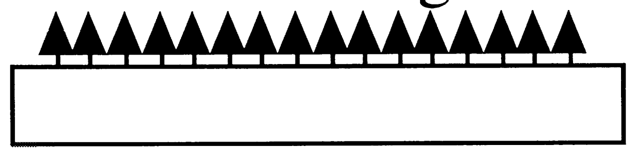


RAMP decompression Experiments

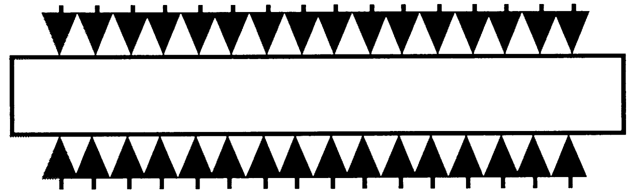
- Water removal and sheet strength were proportional to platen temperature.
- Delamination was supressed when the ramp interval was sufficently long.

Potential Mechanisms

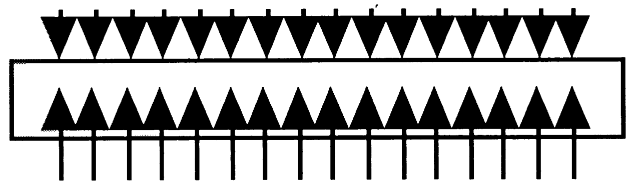
Steam Venting Rate



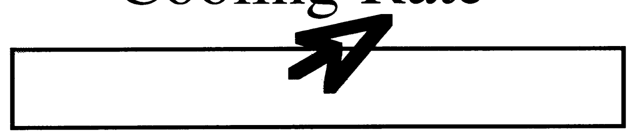
Pressure Restraint



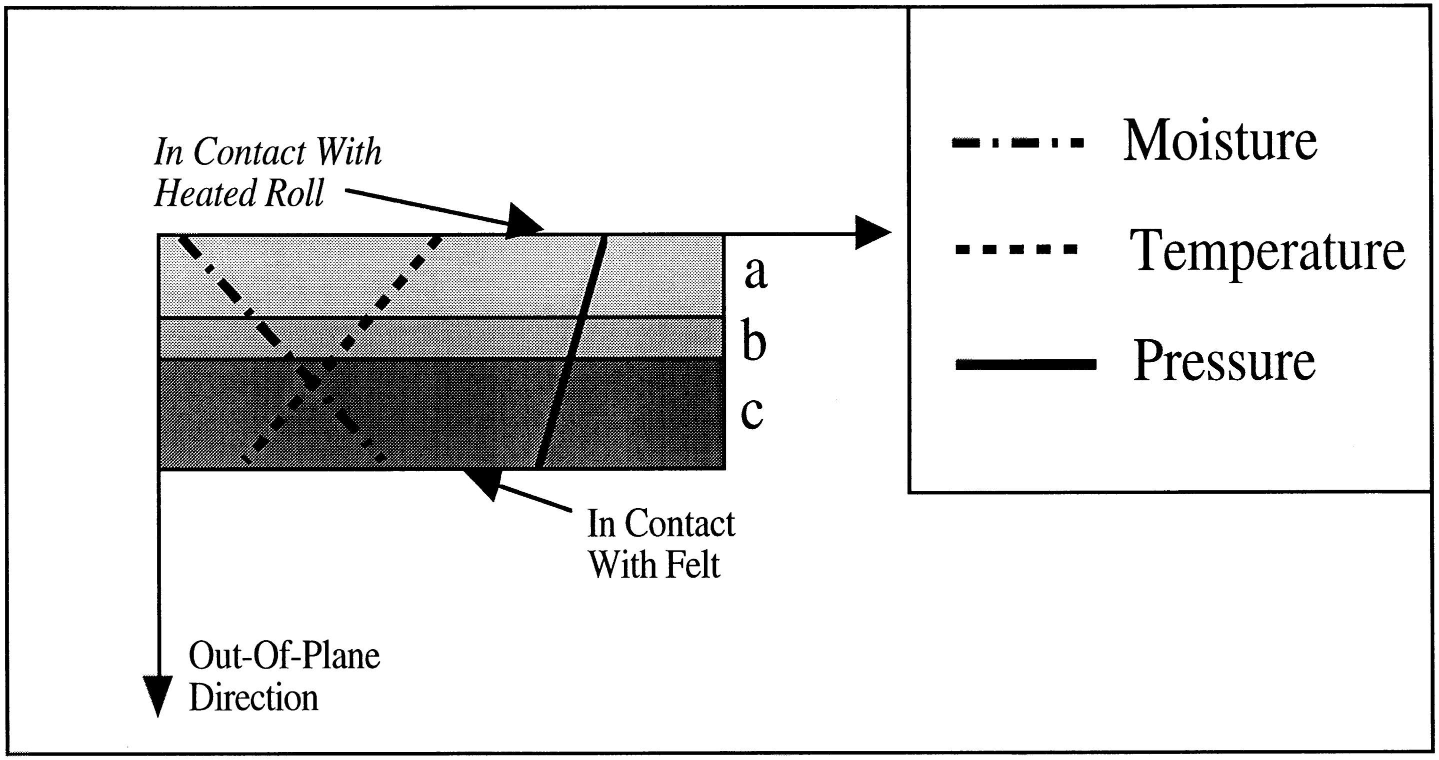
Pressure Difference



Cooling Rate

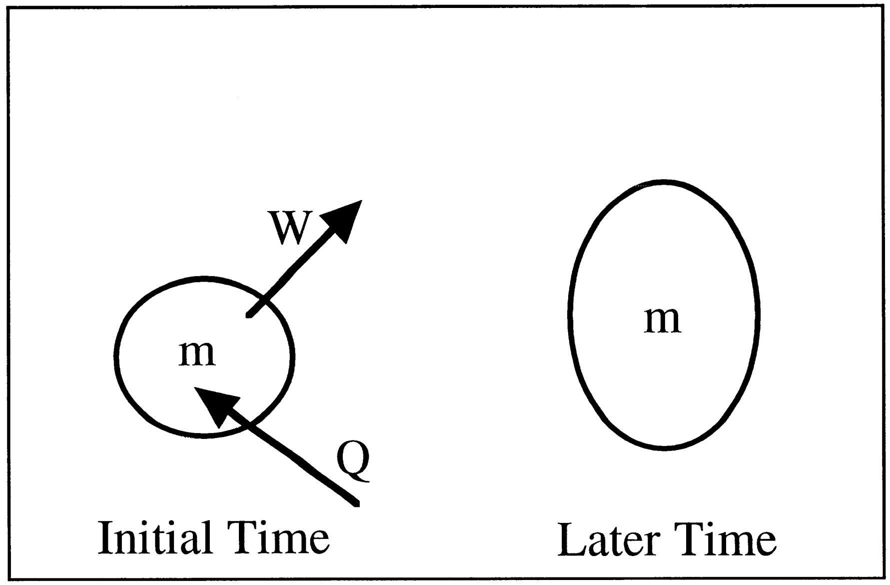


Theoretical Model Concept



Thermodynamic System

- Subcooled liquid in pores is heated while pressure drops.
- Liquid water expands and evaporates.
- Work is done on surroundings.



Mathematical Model

- In The Subcooled Region

$$\frac{dT}{dt} = \frac{\left\{\frac{1}{m}\right\}\frac{\delta Q}{dt} - \left\{\left(\frac{\partial u}{\partial P}\right)_T + P\left(\frac{\partial v}{\partial P}\right)_T\right\}\frac{dP}{dt}}{\left\{\left(\frac{\partial u}{\partial T}\right)_P + P\left(\frac{\partial v}{\partial T}\right)_P\right\}}$$

$$\frac{dV}{dt} = m\left(\left(\frac{\partial v}{\partial P}\right)_T \frac{dP}{dt} + \left(\frac{\partial v}{\partial T}\right)_P \frac{dT}{dt}\right)$$

$$\frac{dW}{dt} = Pm\left[\left(\frac{\partial v}{\partial P}\right)_T \frac{dP}{dt} + \left(\frac{\partial v}{\partial T}\right)_P \frac{dT}{dt}\right]$$

Mathematical Model

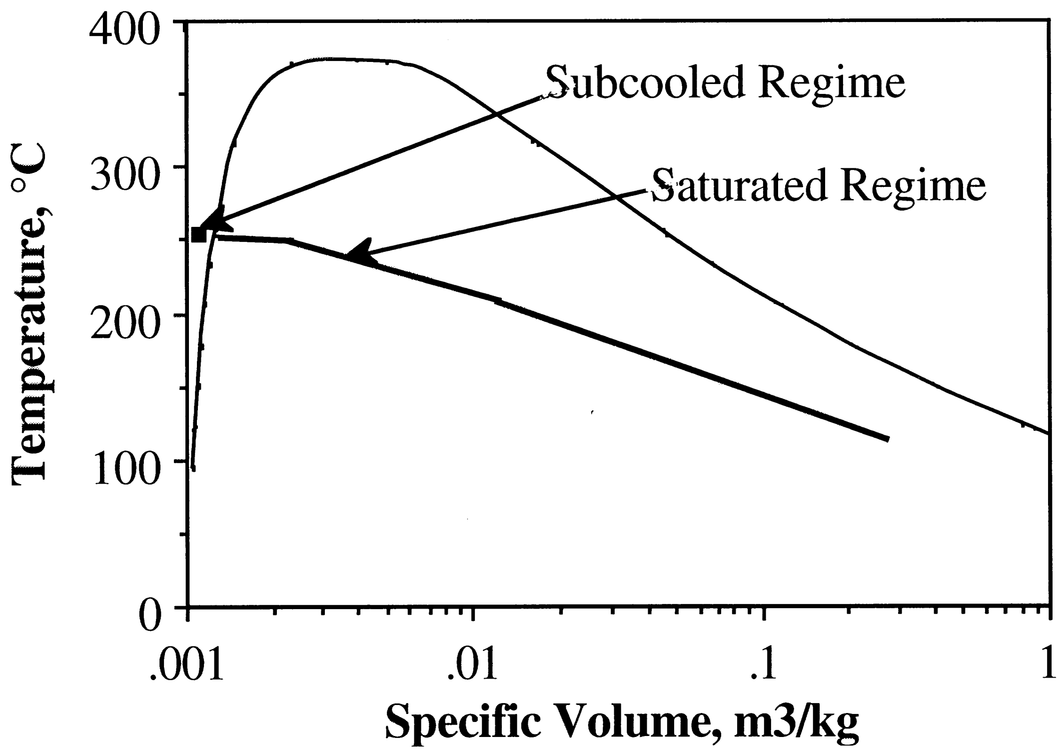
- In The Saturated Region

$$\frac{dm_V}{dt} = \frac{\frac{\delta Q}{dt} - \frac{dP}{dt}\left[m\left(\frac{du_f}{dP} + P\frac{dv_f}{dP}\right) + m_V\left(\frac{du_{fg}}{dP} + P\frac{dv_{fg}}{dP}\right)\right]}{u_{fg} + v_{fg}P}$$

$$\frac{dV}{dt} = v_{fg}\frac{dm_V}{dt} + \frac{dP}{dt}\left[(m - m_V)\frac{dv_f}{dP} + m_V\frac{dv_g}{dP}\right]$$

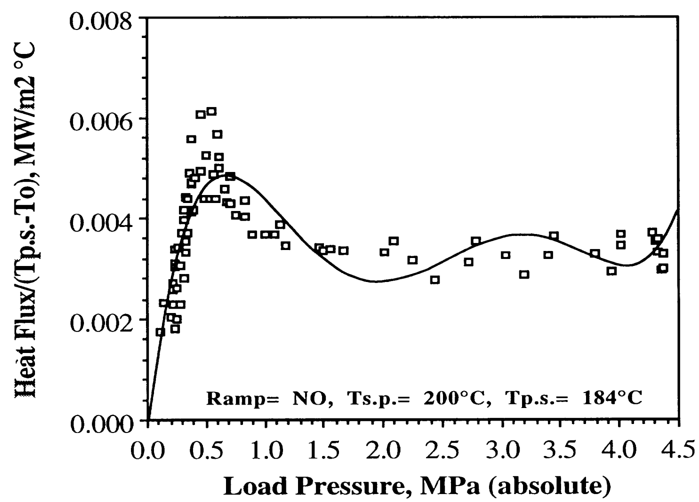
$$\frac{dW}{dt} = v_{fg}P\frac{dm_V}{dt} + P\frac{dP}{dt}\left[m\frac{dv_f}{dP} + m_V\frac{dv_{fg}}{dP}\right]$$

Evaporative Cooling Process



Heat Flux To Heated Surface During Nip Opening

- Increases with platen temperature.
- Decreases with load as nip opens.
- Similar to contact resistance problems.
- Suggests vapor layer at sheet-platen interface.



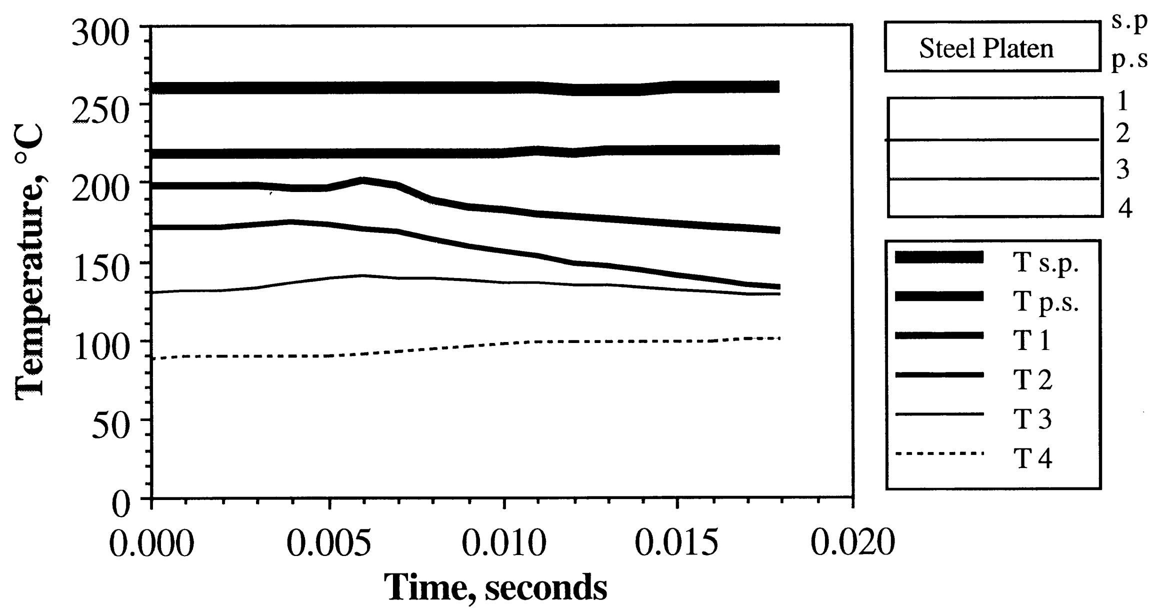
Upper Estimate Of System Heat Transfer

- An upper estimate.
- Strictly true only for steady state heat transfer.
- Neglects conduction and convection effects within sheet.

$$\frac{\delta Q}{dt} = \frac{HeatFlux}{\left(\frac{100 - \%S}{\%S}\right)(BWt)}$$

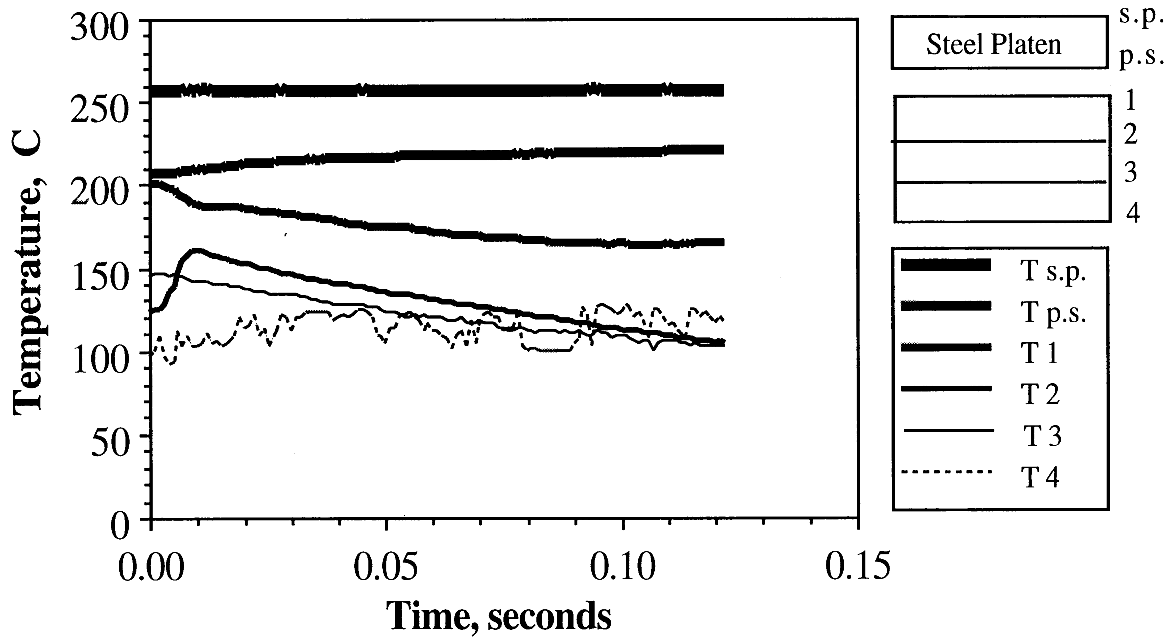
Measured Internal Sheet Temperatures

- Ramp Case = NO.
- $T_{s.p.}$= 260°C.
- T_2 (end) = 135°C
- t (trans) = 0.005 s



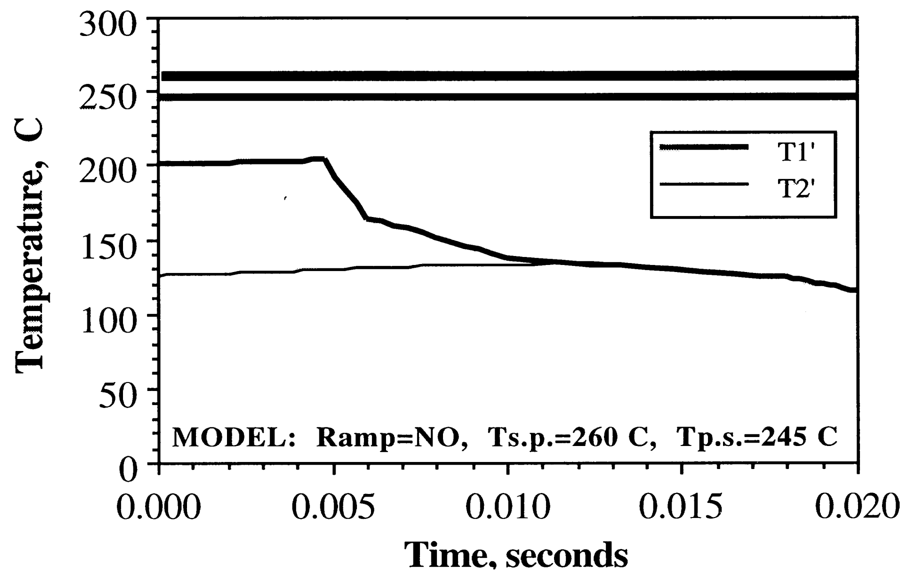
Measured Internal Sheet Temperatures

- Ramp Case = A.
- Ts.p.= 260 C.
- T_2 (end) = 110 C
- t (trans) = 0.01s



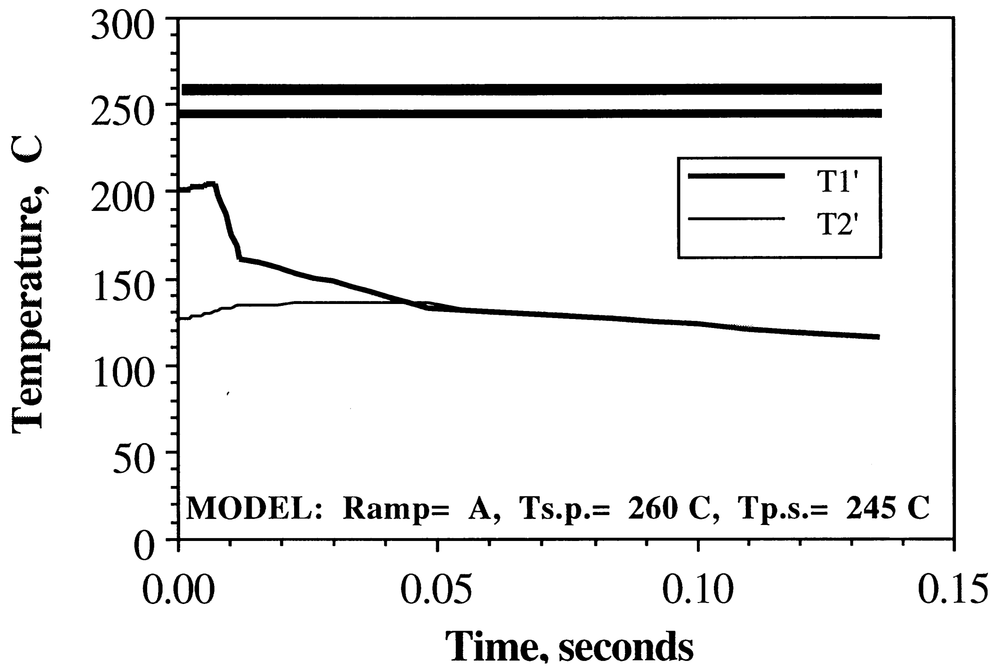
Computed Internal Temperatures

- Ramp Case = NO.
- Ts.p.= 260 C.
- T_2 (end) = 120 C
- t (trans) = 0.011 s



Computed Internal Temperatures

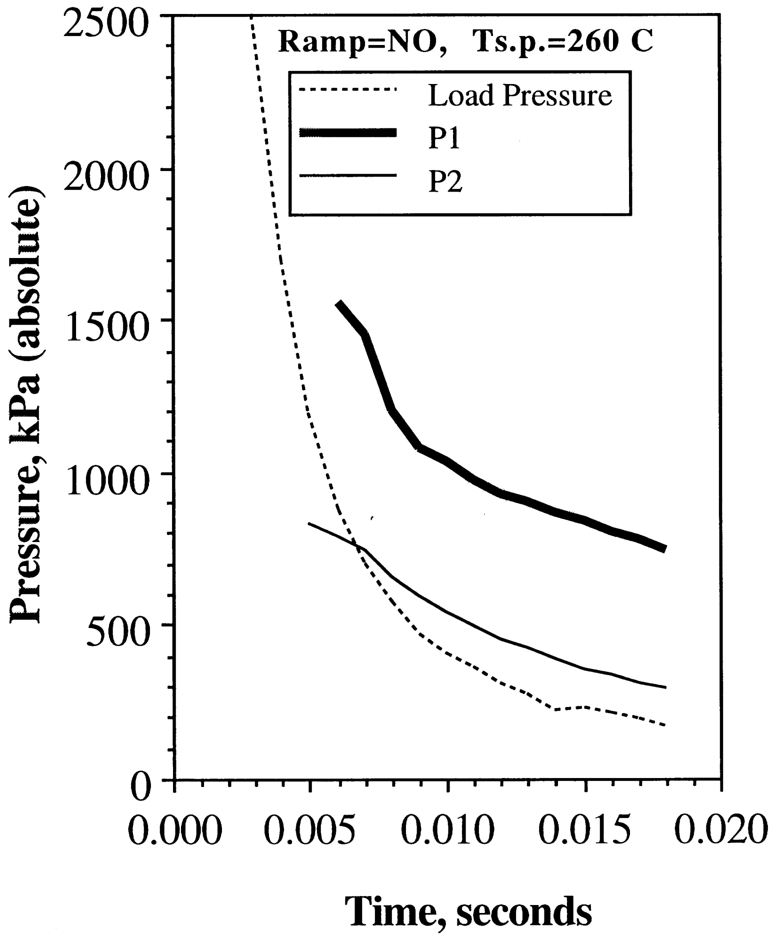
- Ramp Case = A.
- Ts.p.= 260 C.
- T_2 (end) = 120 C
- t (trans) = 0.045 s



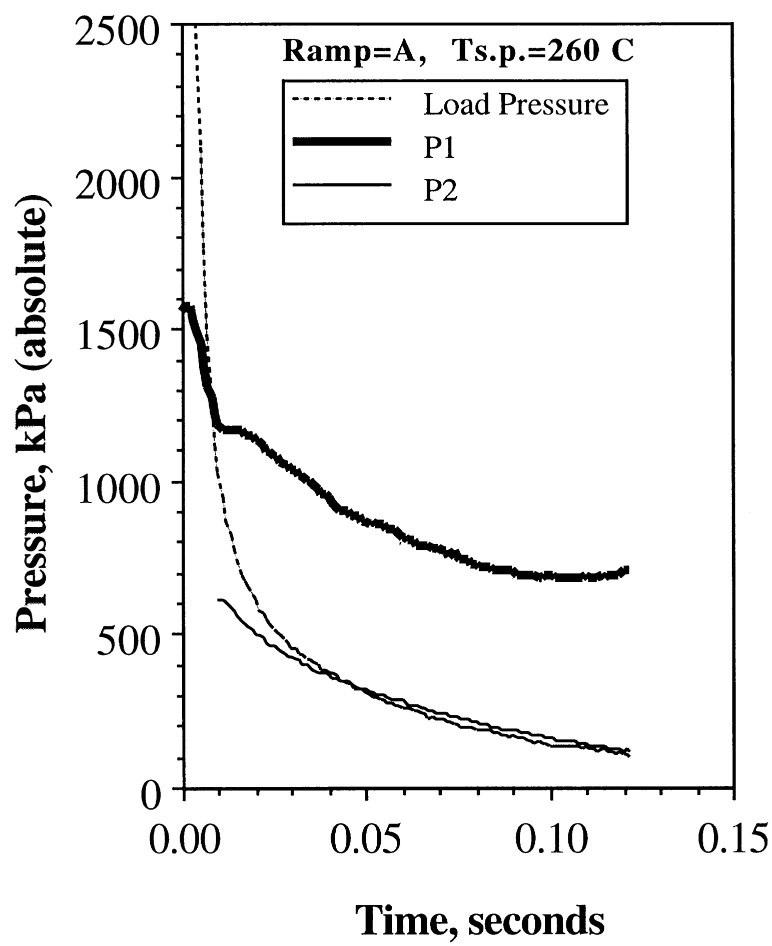
Internal Sheet Pressures

- When temperature at a given location in the sheet rapidly decreases with increased time, that location has experienced a phase change from subcooled liquid to saturated mixture.
- In saturated region, pressure is directly related to temperature and is the saturation pressure at that measured temperature.

Internal Pressures For RAMP =NO, 260 C



Internal Pressures For RAMP =A, 260 C



Increasing Ramp Length

- Decreases dP/dt, while dQ/dt does not increase substantially since pressures are low.
- Results in lower internal sheet temperatures and pressures.
- Exit pressure differential between inside and outside of sheet is therefore reduced.

GOALS FOR FY: 1996 - 1997

- Investigate mechanisms by which HAPID eliminates sheet delamination. This is ongoing M.S. Thesis work that is expected to be completed by May 1996.

GOALS FOR FY: 1996 - 1997

- Develop fundamental understanding of internal and external heat transfer, vapor venting, and sheet expansion during nip opening.
- Incorporate into improved model to predict temperature and pressure as a function of time and z-direction location in the sheet. Complete by September 1996.

GOALS FOR FY: 1996 - 1997

- Use the improved model and strategic experiments to determine guidelines for optimizing practical load decompression profiles for various grades, furnishes, and basis weights. Complete by March 1997.

FUNDAMENTALS OF COATING SYSTEMS

SLIDE MATERIAL

FOR

PROJECT F003

March 18 - 19, 1996
Institute of Paper Science and Technology
Atlanta, Georgia

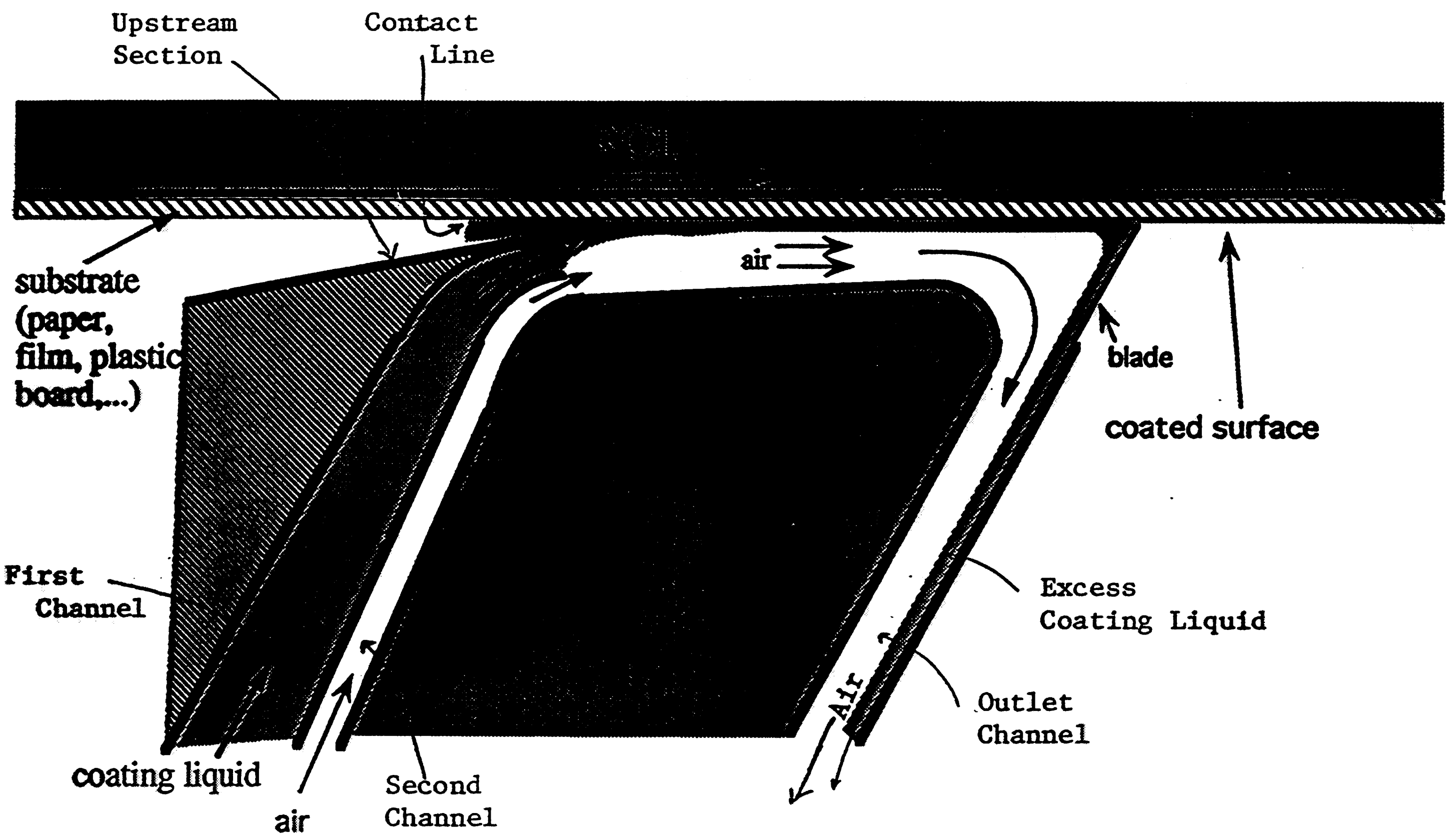
Date: Spring 1996
Project Title: Fundamentals of Coating Systems
Principal Investigator: C. Aidun
Budget (FY 95-96): $46,000
Project No.: 3674

M.S. students: 2
Ph.D. students: 3

OBJECTIVES:

(1) To investigate the cause and origin of coat weight nonuniformities reported in high-speed blade coating of paper and board,

(2) to explore novel coating systems for application of a more uniform coat weight profile at higher machine speeds.



Schematic of the Modified Vortex Free Coater

Figure 1

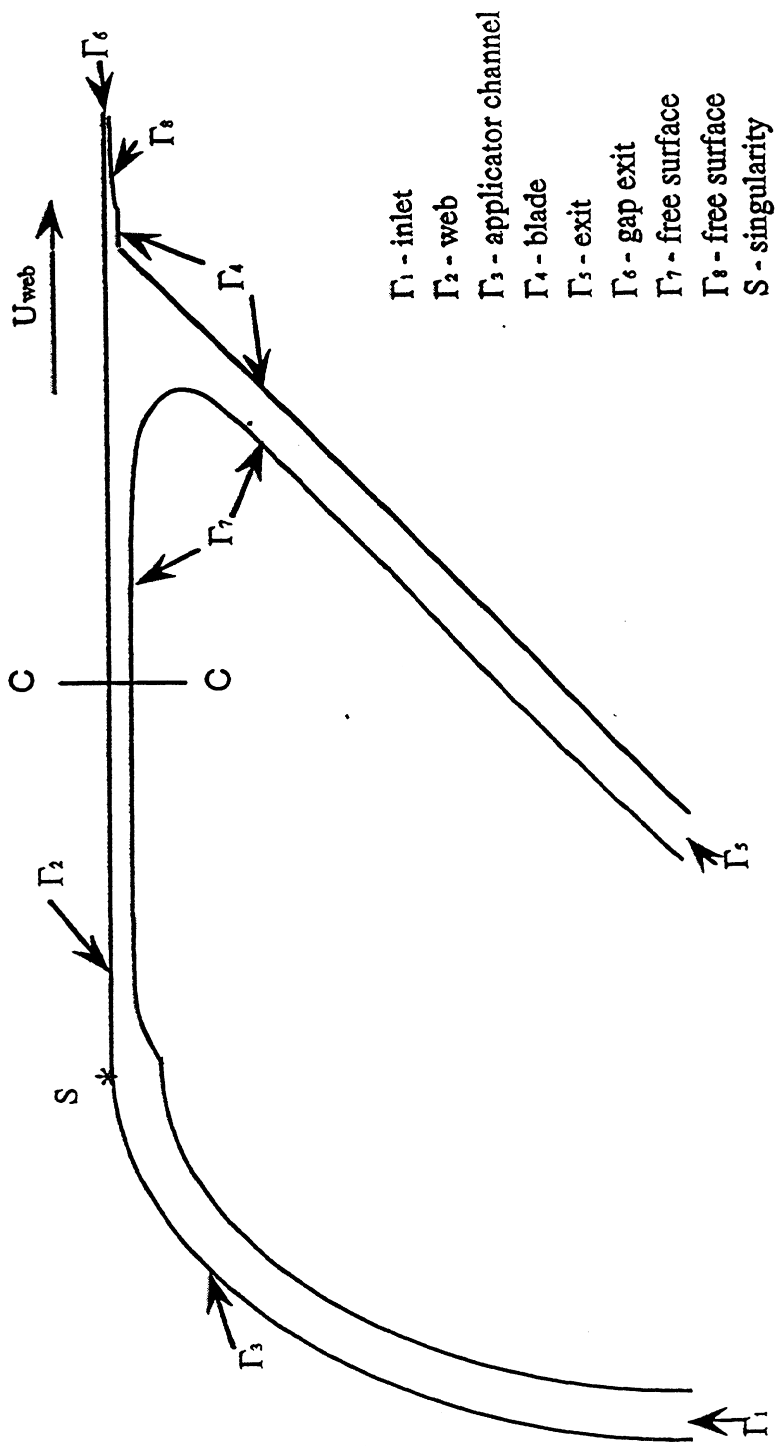

U_{web}
Γ_6
Γ_8
Γ_4
Γ_7
C
C
Γ_2
S
Γ_5
Γ_3
Γ_1
Γ_1 - inlet
Γ_2 - web
Γ_3 - applicator channel
Γ_4 - blade
Γ_5 - exit
Γ_6 - gap exit
Γ_7 - free surface
Γ_8 - free surface
S - singularity

Table 1: Fluid Parameters

ρ	density	1200 kg/m^3
μ_o	zero shear rate viscosity	1.0 kg/(m-s)
μ_∞	infinite shear rate viscosity	0.05 kg/(m-s)
γ	surface tension	0.05 kg/s^2
c	Carreau exponent	0.65
K	time constant	0.01 s
U_{web}	web velocity	varies from 15-30 m/s
U_{inlet}	centerline velocity on inlet	varies from 2-5 m/s
q_{inlet}	inlet flowrate	varies from 4-7 l/s/m

Table 2: Geometry Parameters

L_{inlet}	inlet length	0.0025 m
L_{gap}	gap length	50 E-6 m
L_{ace}	applicator channel exit	0.5 mm
L_{thick}	blade thickness	1.25 mm
L_{blade}	blade length (modeled)	60.104 mm
L_{web}	web length (modeled)	59.551 mm
$<_{blade}$	angle of blade	45°
C_t	coating thickness	O(10 μm)
W_t	vertical distance from web to free surface at C-C	O(100 μm)

Table 3: Dimensionless Quantities

Re	Reynolds Number	$Re = \frac{\rho U_{web} L_{in}}{\mu}$
Ca	Capillary Number	$Ca = \frac{\mu U_{web}}{\gamma}$
We	Weber Number	$We = \frac{1}{Re Ca} = \frac{\gamma}{\rho U_{web}^2 L_{in}}$

Table 4: Case Study - Effect of Flowrate Variation

Case	U_{web}	U_{inlet}	q_{inlet}	q_{film}	q_{exit}	C_t	W_t	Re	Ca	We
	m/s	m/s	l/s/m	l/s/m	l/s/m	µm	µm			1/ReCa
C4V20	20	2.4	4	.5481175	3.61508	27.465	208.4447	60	400	1/24000
C5V20	20	3	5	.550354	4.611883	27.575	259.0522	60	400	1/24000
C6V20	20	3.6	6	.552128	5.60895	27.66575	309.472	60	400	1/24000
C7V20	20	4.2	7	.553462	6.52	27.7325	354.6727	60	400	1/24000

Table 5: Case Study - Effect of Web Speed Variation

Case	U_{web} m/s	U_p m/s	q_{inlet} l/s/m	q_{film} l/s/m	C_t µm	Re	Ca	We 1/ReCa
C6V15	15	3.6	6	0.409921	27.42438	45	300	1/13500
C6V20	20	3.6	6	0.552128	27.66575	60	400	1/24000
C6V25	25	3.6	6	0.695813	27.873	75	500	1/37500
C6V30	30	3.6	6	0.841083	28.0655	90	600	1/54000
C7V15	15	4.2	7	0.410793	27.48275	45	300	1/13500
C7V20	20	4.2	7	0.553462	27.7325	60	400	1/24000
C7V25	25	4.2	7	0.698024	27.9615	75	500	1/37500
C7V30	30	4.2	7	0.844202	28.1695	90	600	1/54000

Table 6: Conversion to Dimensional Units

dimensionless quantity	scale	web speed	multiply by	dimensional units
p^*	$\rho U_s^2 = \rho U^2_{web}$	15 m/s	0.270 E+6	Pa
p^*	$\rho U_s^2 = \rho U^2_{web}$	20 m/s	0.480 E+6	Pa
p^*	$\rho U_s^2 = \rho U^2_{web}$	25 m/s	0.750 E+6	Pa
p^*	$\rho U_s^2 = \rho U^2_{web}$	30 m/s	1.080 E+6	Pa
q^*	$U_s L_s = U_{web} L_{inlet}$	15 m/s	37.5	l/s/m
q^*	$U_s L_s = U_{web} L_{inlet}$	20 m/s	50.0	l/s/m
q^*	$U_s L_s = U_{web} L_{inlet}$	25 m/s	62.5	l/s/m
q^*	$U_s L_s = U_{web} L_{inlet}$	30 m/s	75.0	l/s/m
u_i^*	$U_s = U_{web}$	15 m/s	15	m/s
u_i^*	$U_s = U_{web}$	20 m/s	20	m/s
u_i^*	$U_s = U_{web}$	25 m/s	25	m/s
u_i^*	$U_s = U_{web}$	30 m/s	30	m/s
x_i^*	$L_s = L_{inlet}$	all	0.0025	m

Figure 4

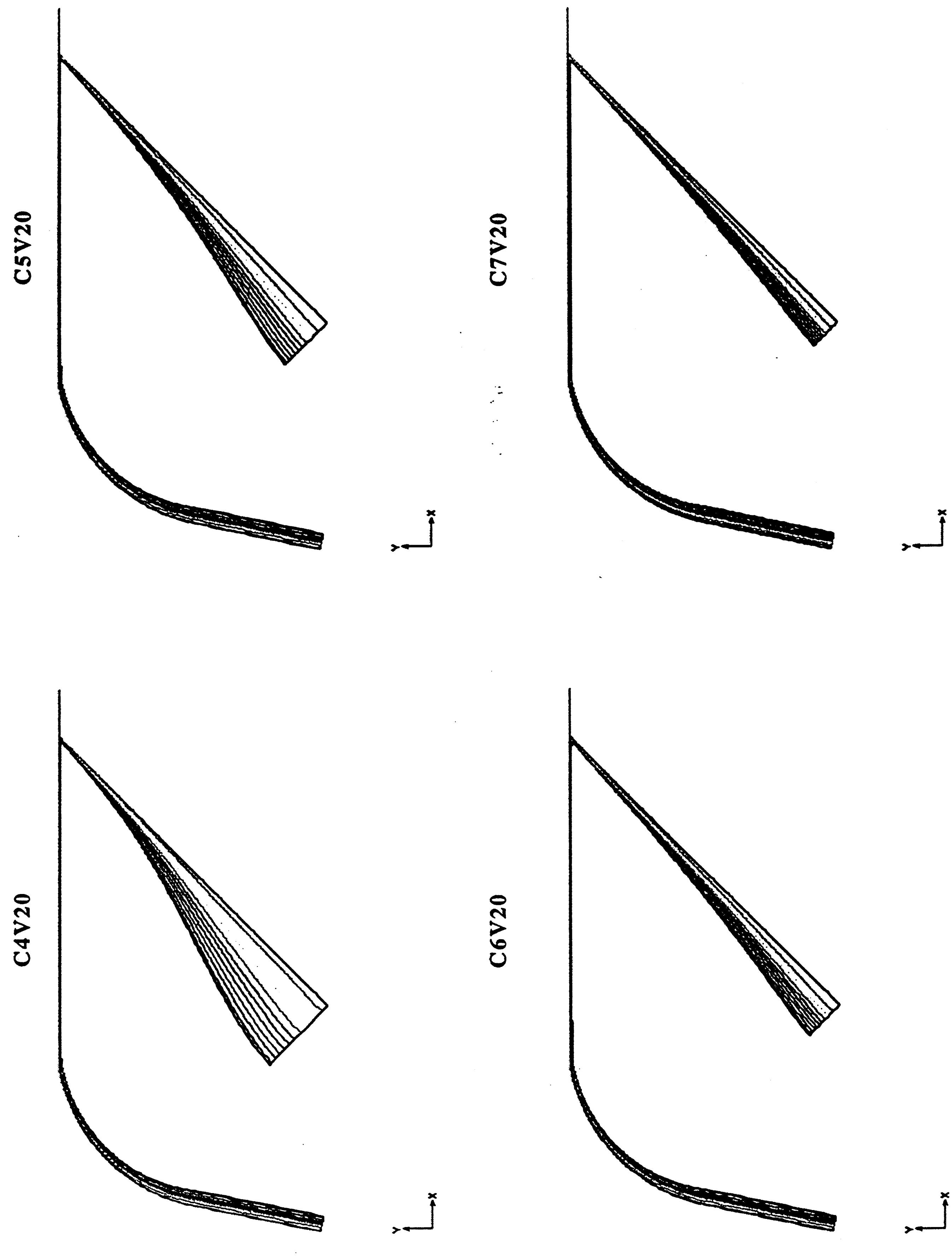


Figure 6

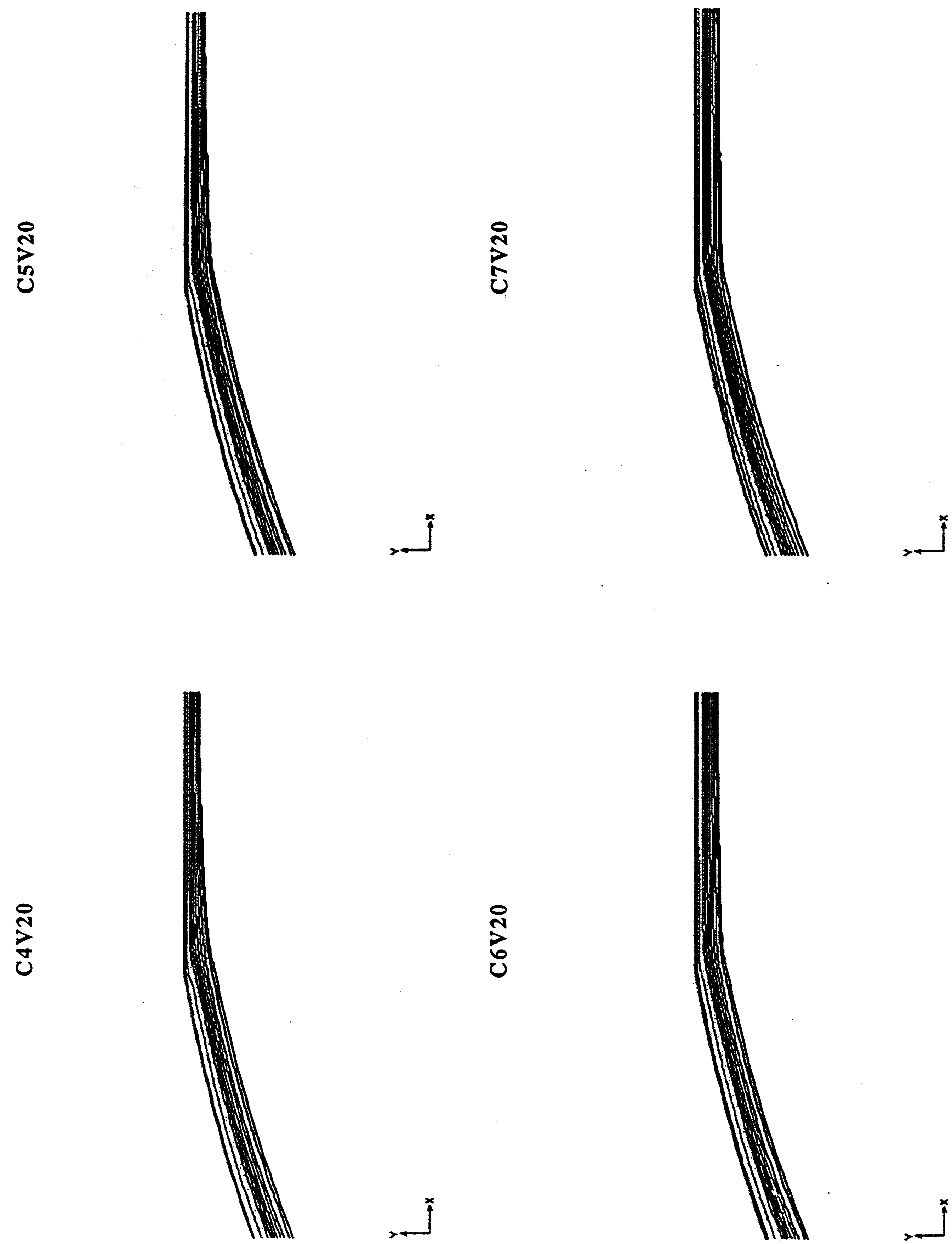


Figure 10

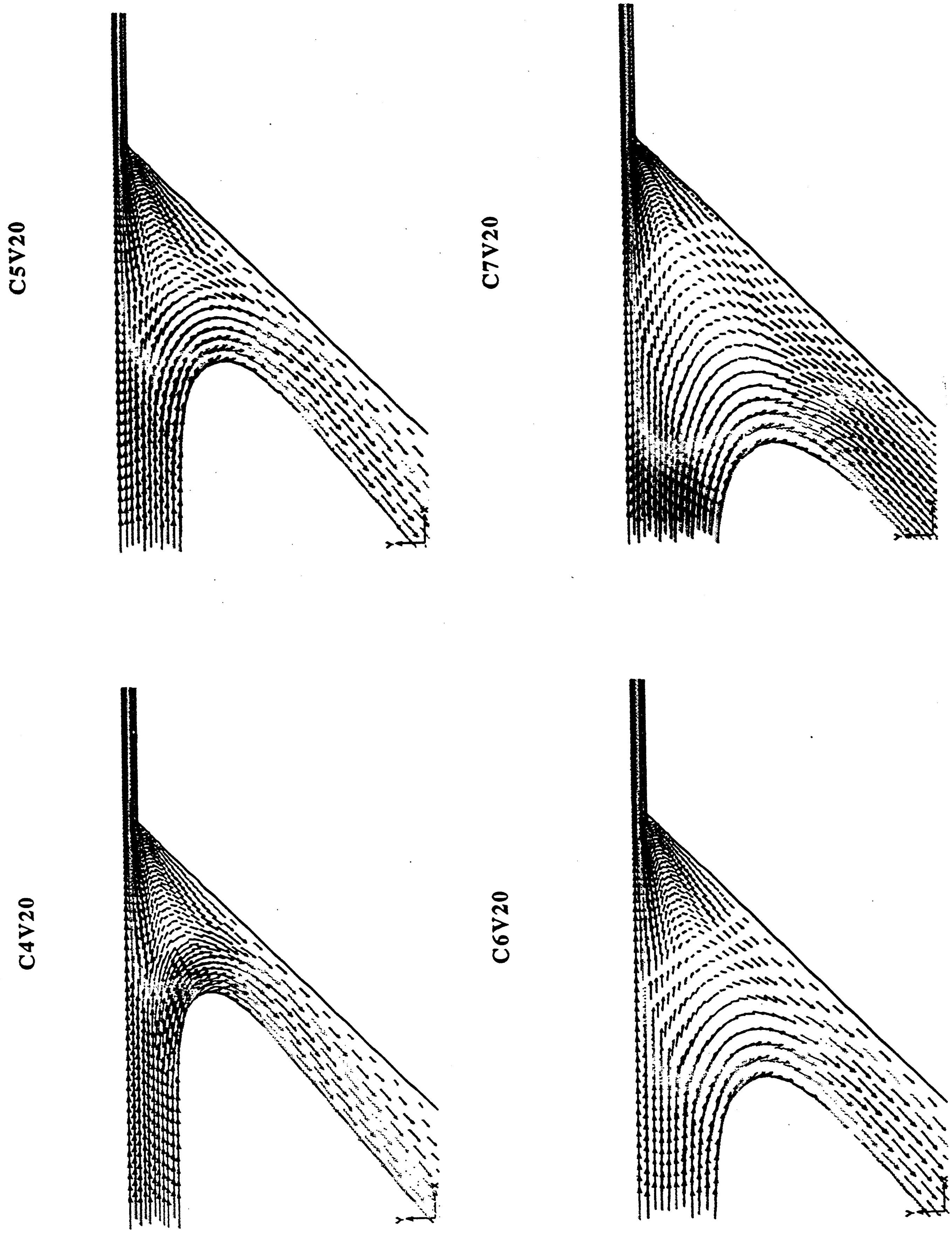
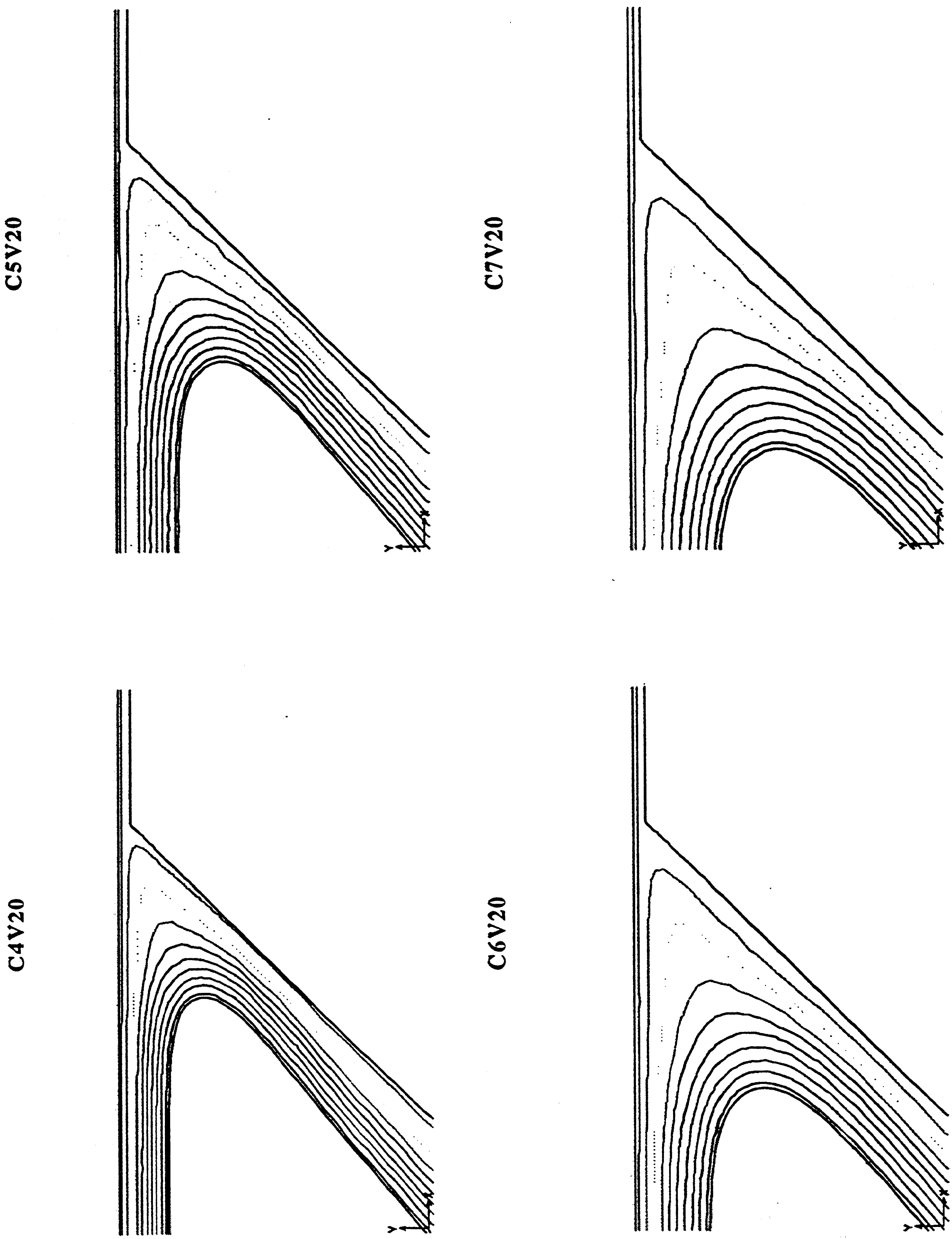


Figure 9



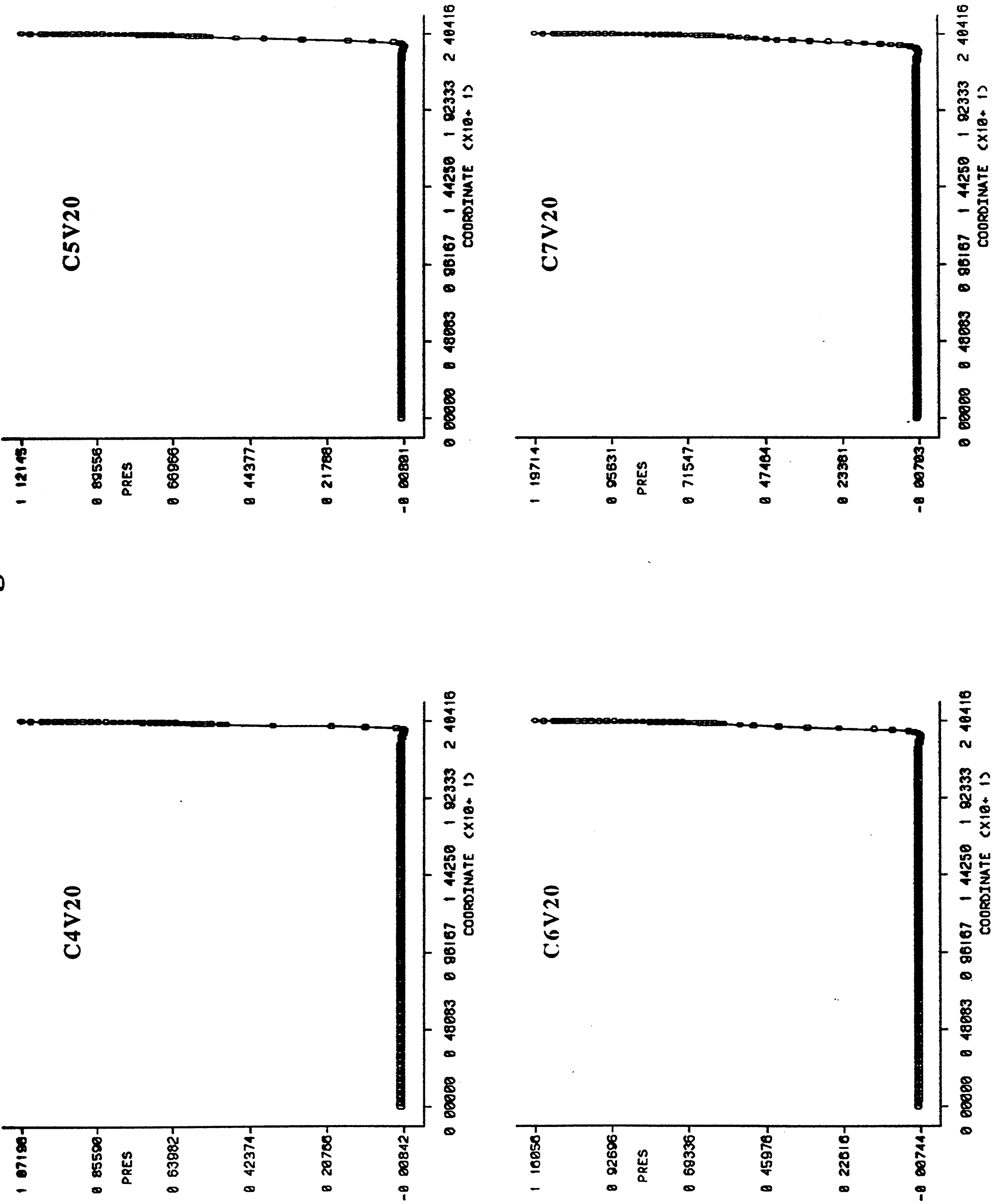


Figure 18

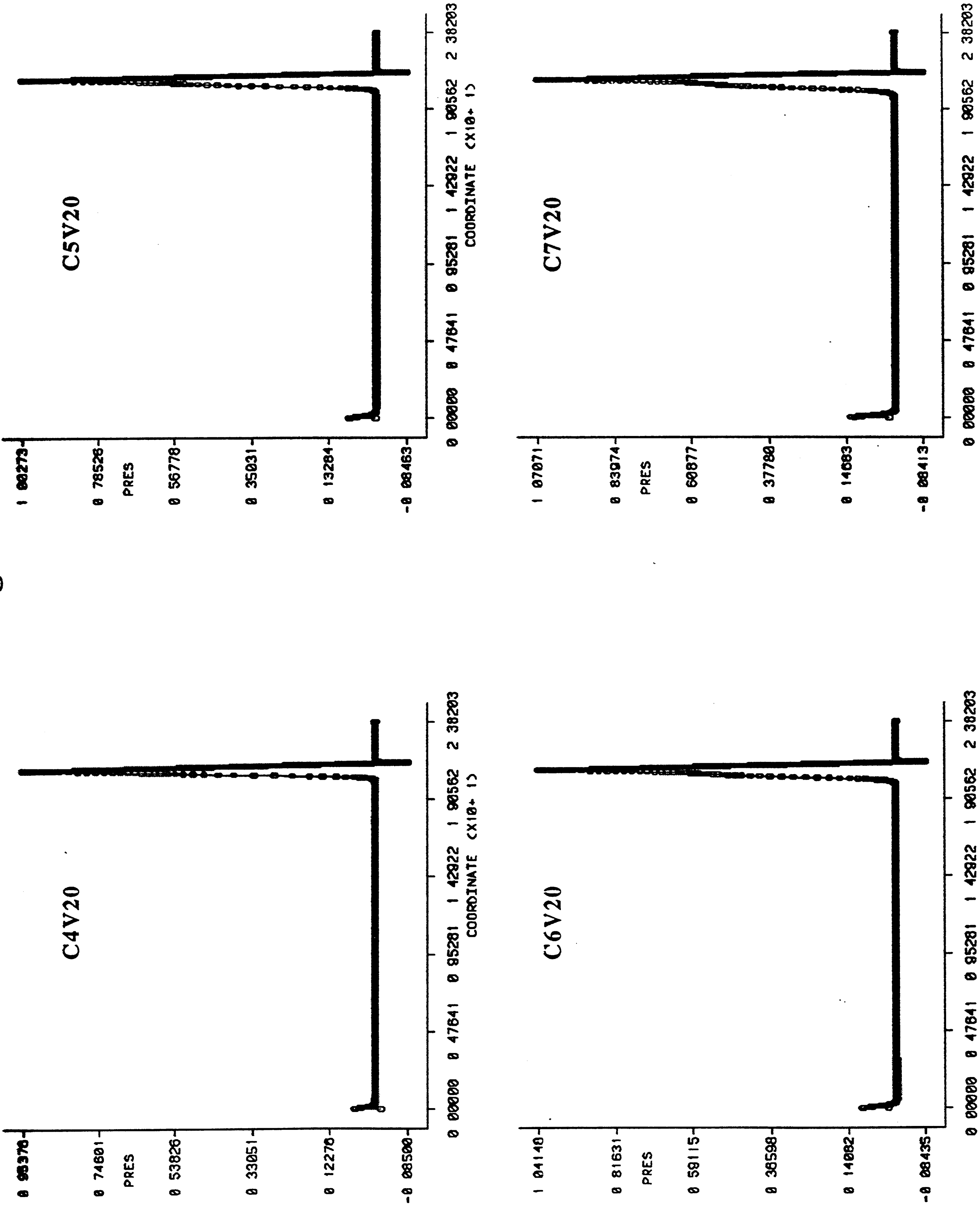


Figure 19

Figure 20

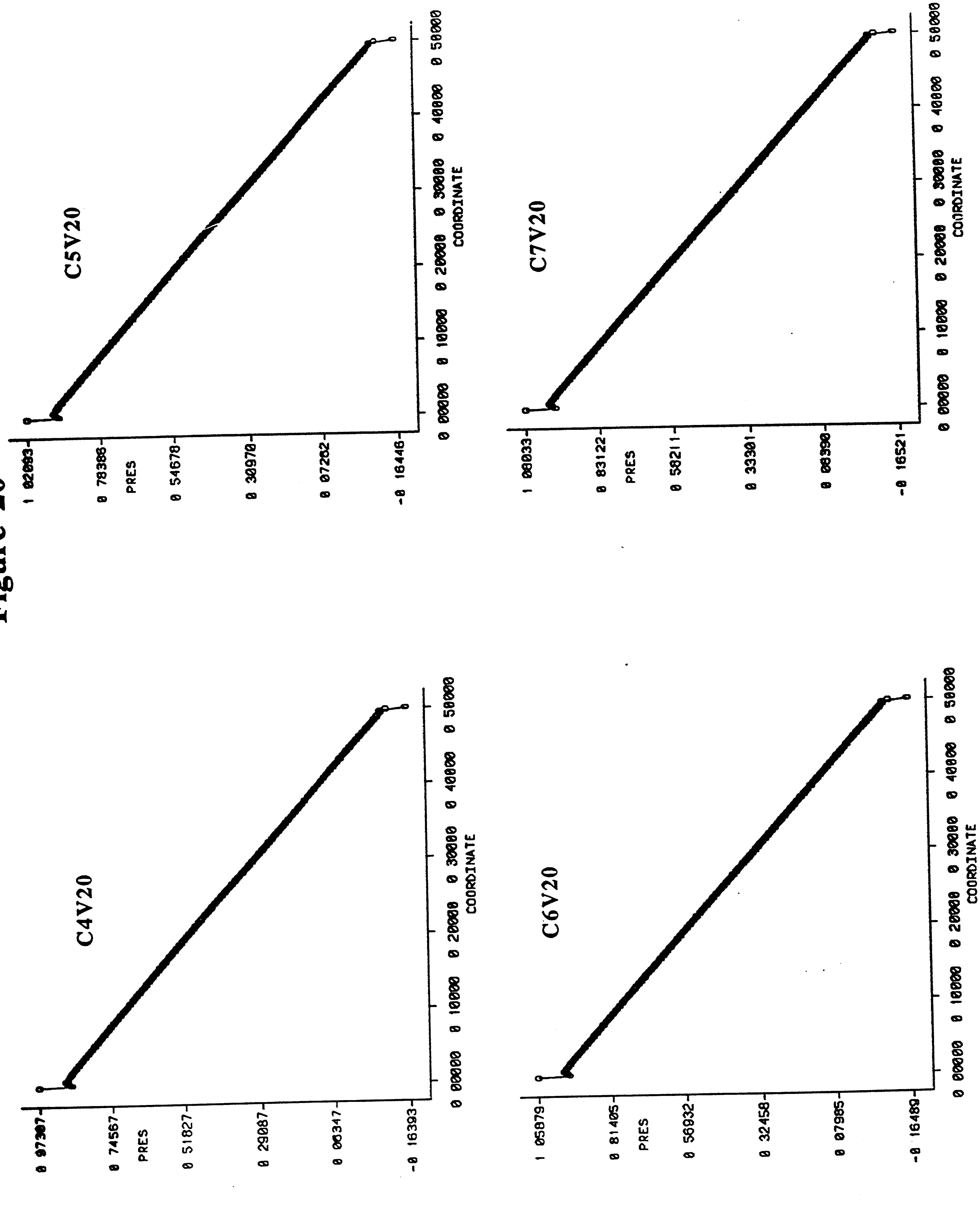


Figure 21

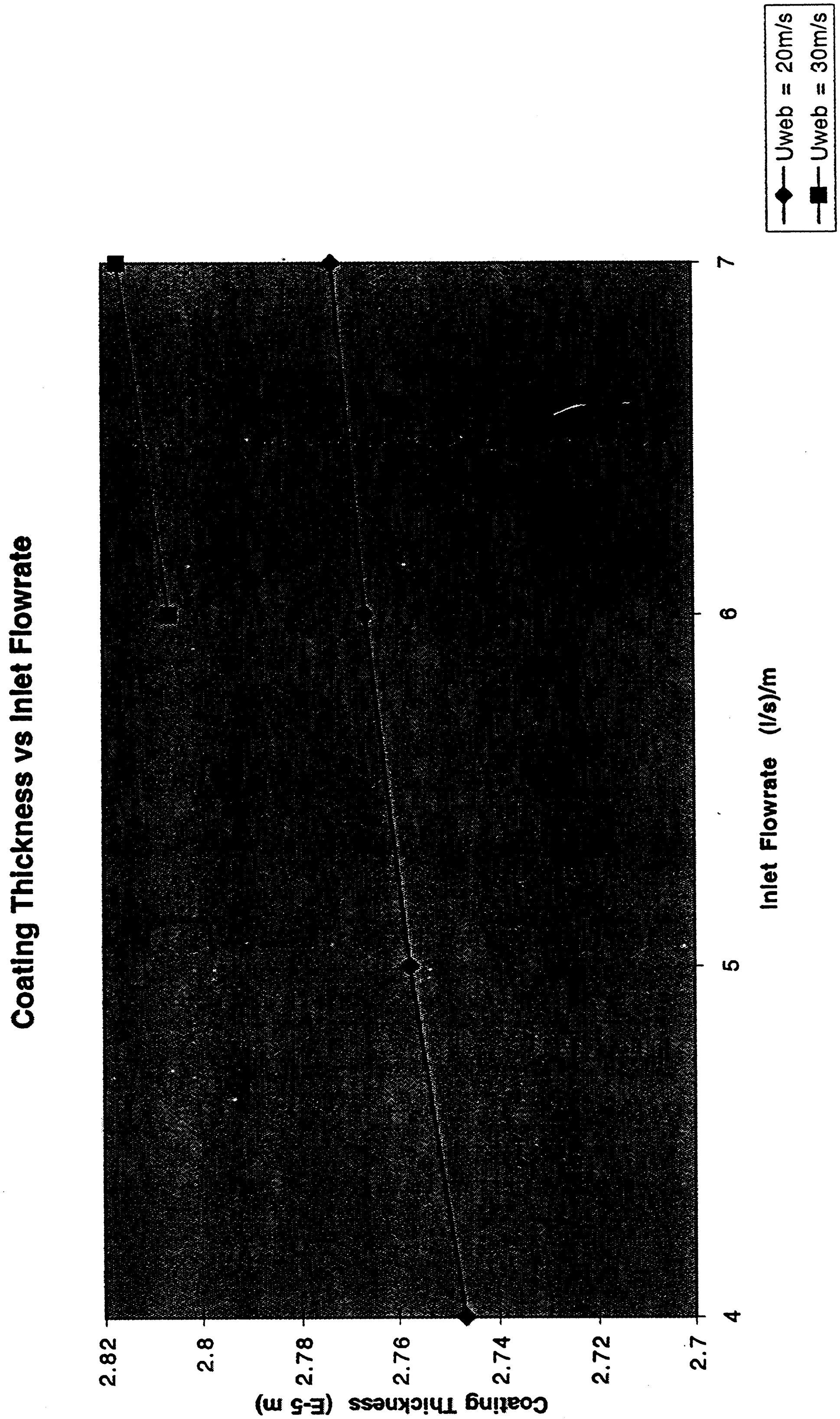

Coating Thickness vs Inlet Flowrate
Coating Thickness (E-5 m)
2.82
2.8
2.78
2.76
2.74
2.72
2.7
4
5
6
7
Inlet Flowrate (l/s)/m
Uweb = 20m/s
Uweb = 30m/s

Figure 22

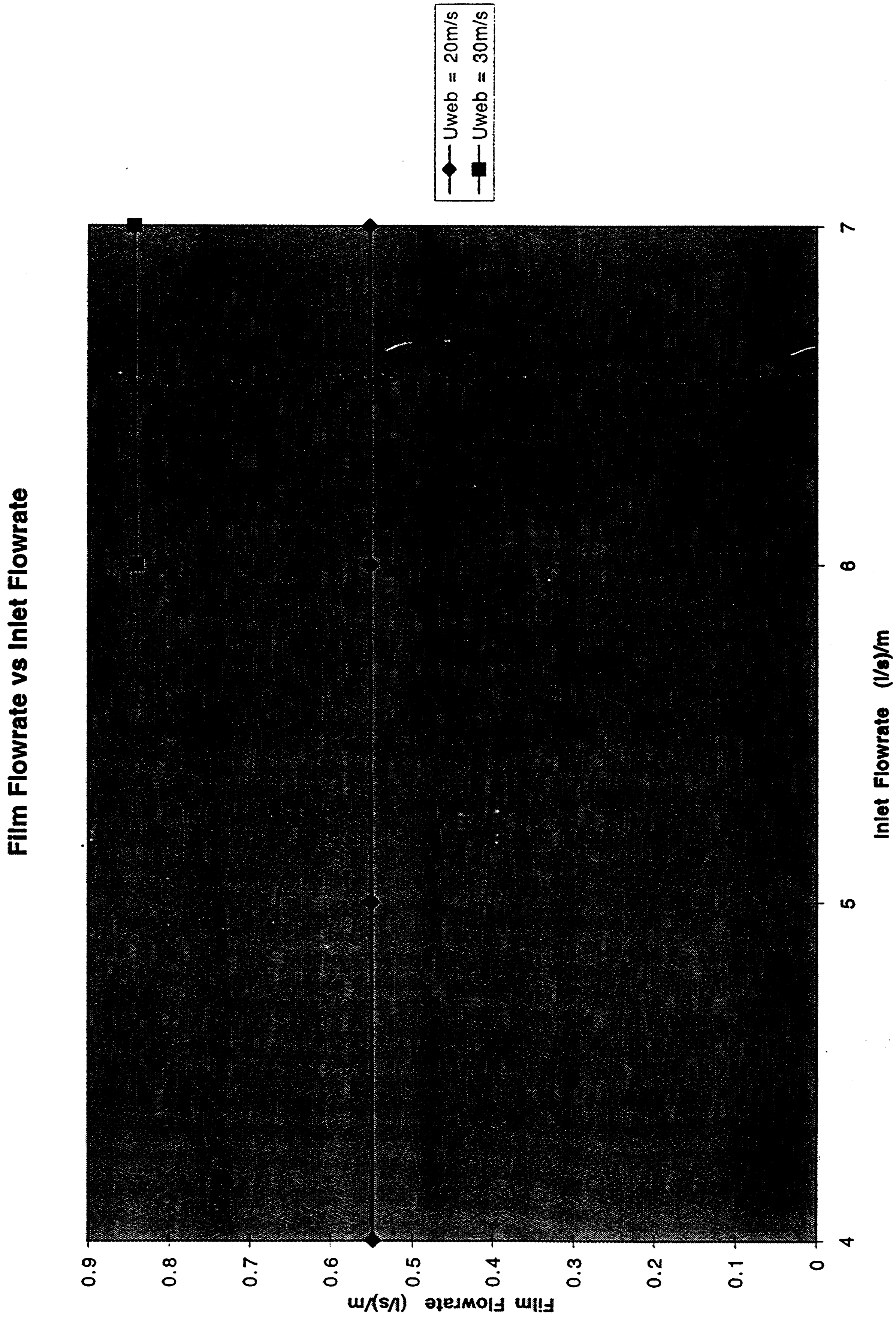
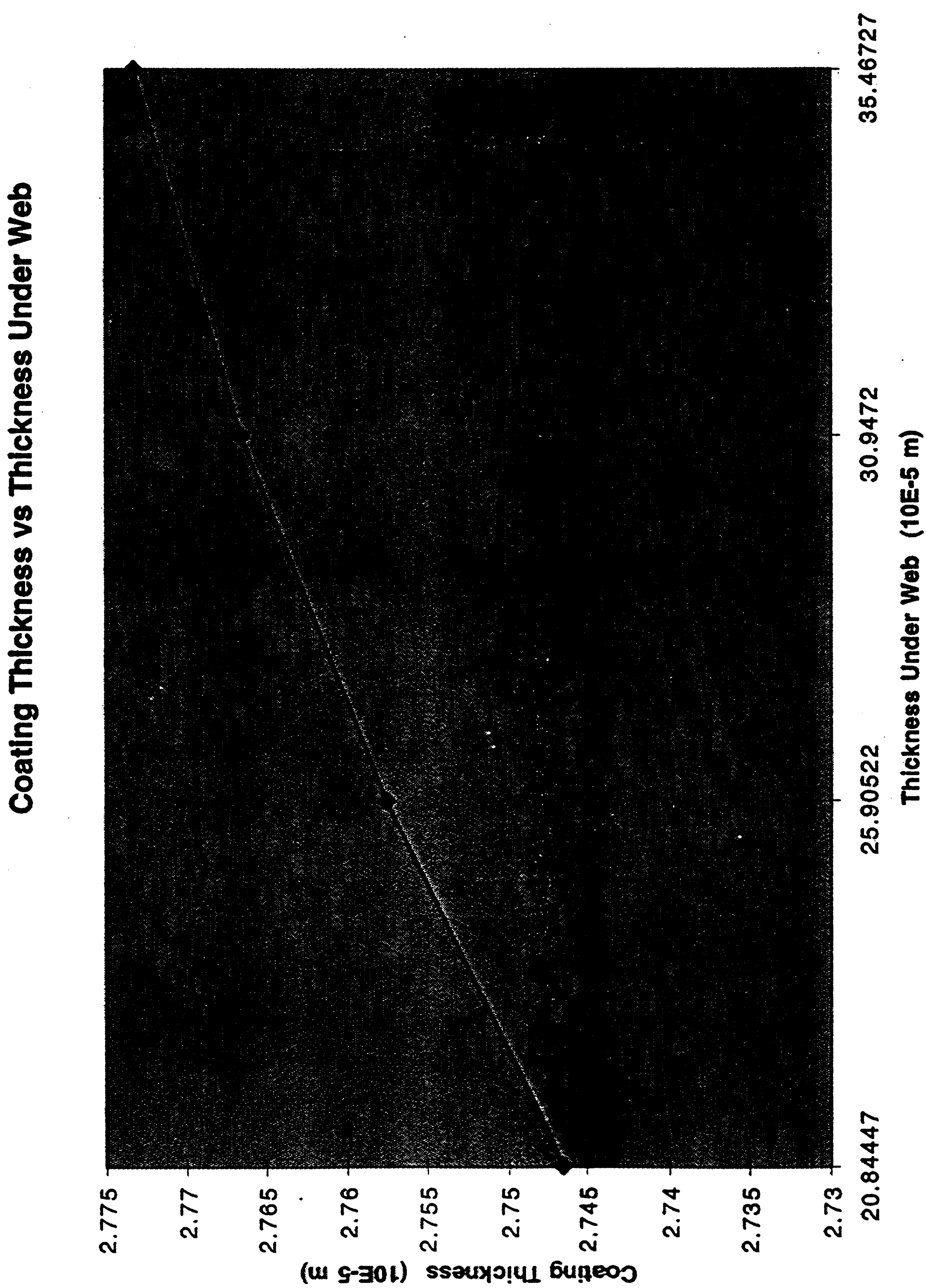

Film Flowrate vs Inlet Flowrate
Uweb = 20m/s
Uweb = 30m/s
Film Flowrate (l/s)/m
Inlet Flowrate (l/s)/m
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
5
6
7

Figure 23


Coating Thickness vs Thickness Under Web
Coating Thickness (10E-5 m)
2.775
2.77
2.765
2.76
2.755
2.75
2.745
2.74
2.735
2.73
20.84447
25.90522
30.9472
35.46727
Thickness Under Web (10E-5 m)

AIR/SHEET INTERACTIONS

SLIDE MATERIAL

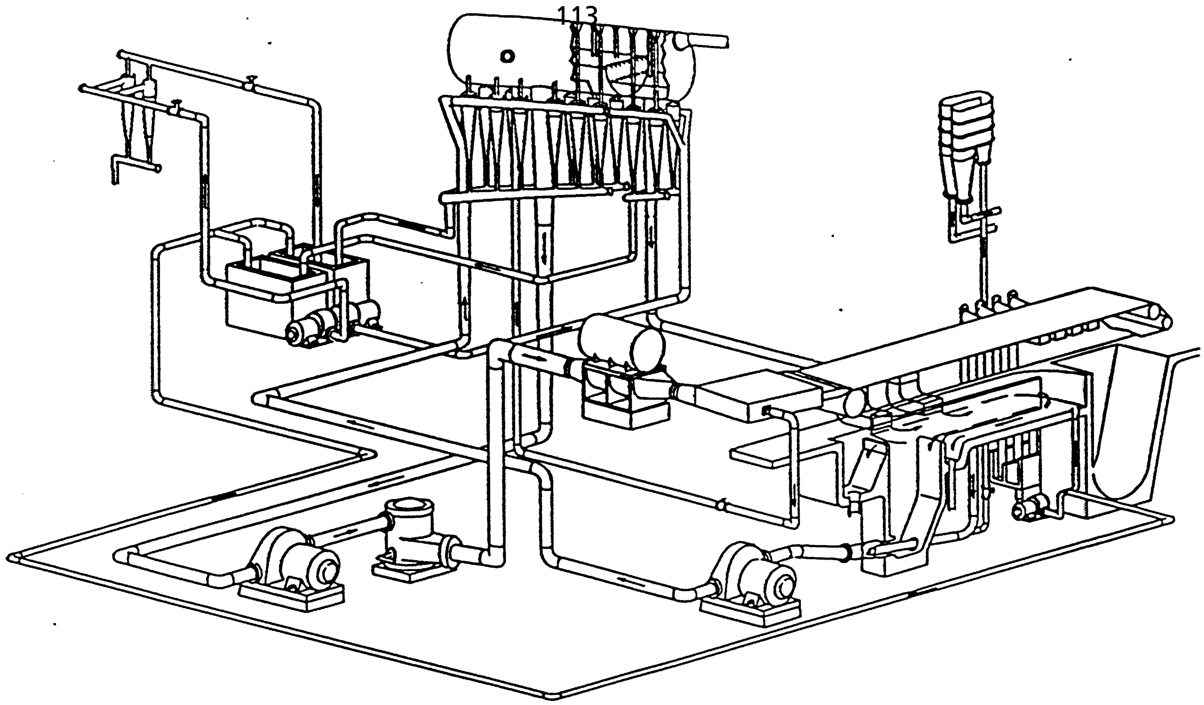
FOR

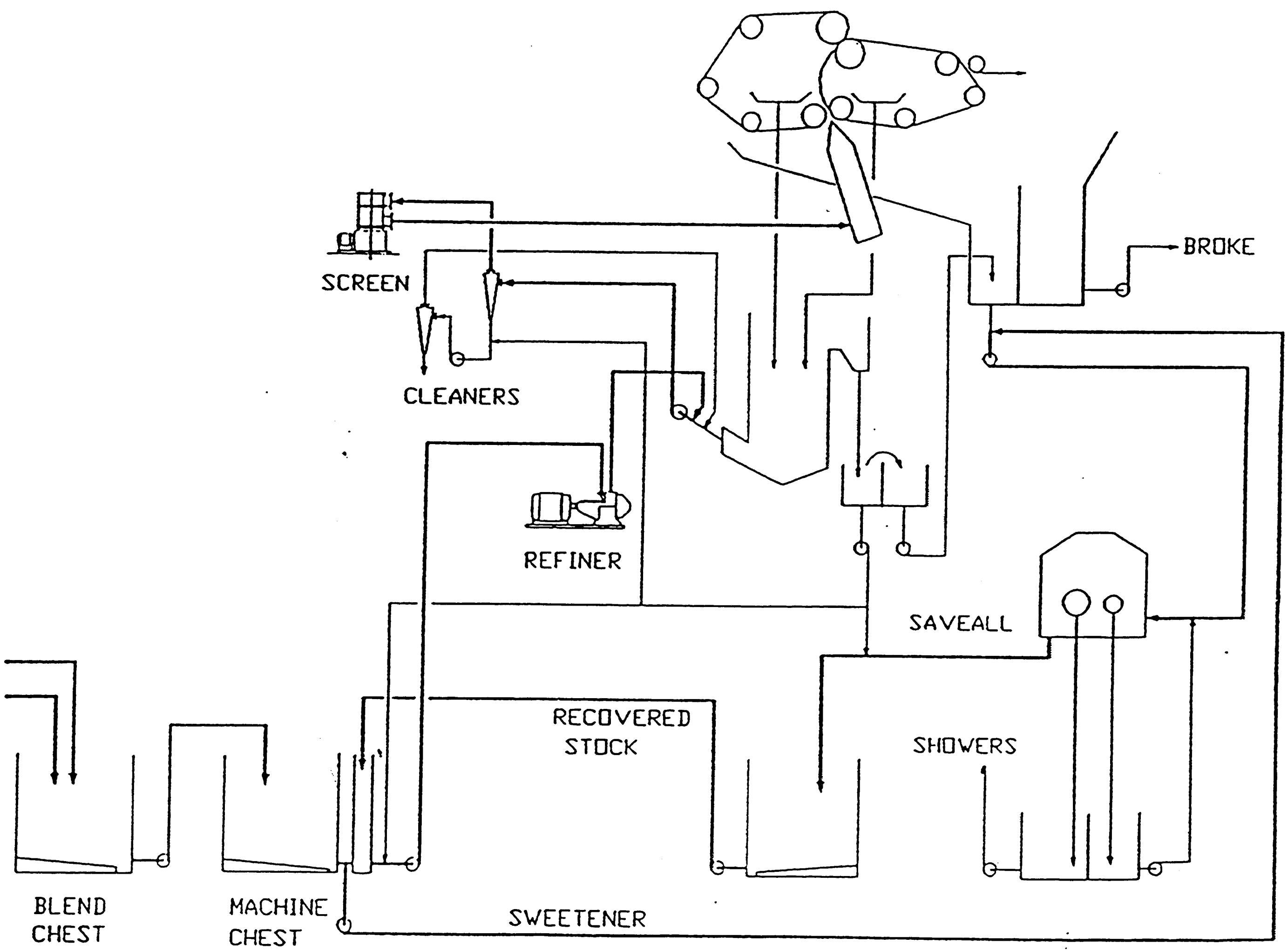
PROJECT F006

March 18 - 19, 1996
Institute of Paper Science and Technology
Atlanta, Georgia

Approach Flow System Project

Xiaodong Wang, Assistant Professor
Institute of Paper Science and Technology



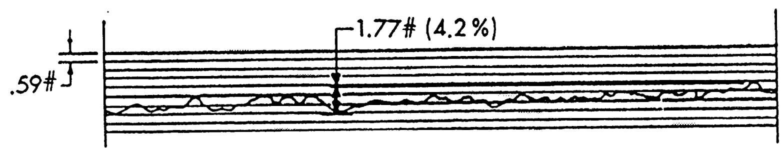


Twin Wire Machine System

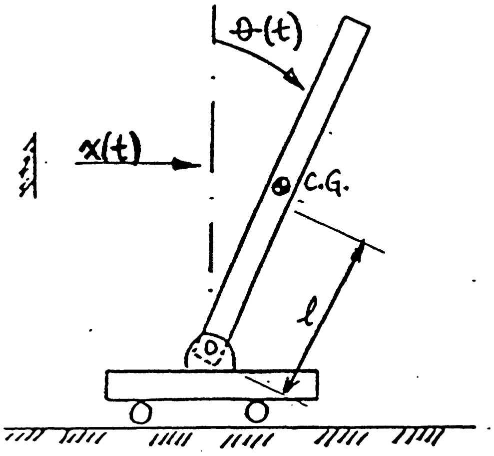
Conglomeration of Components

- Hard to follow guidelines;
- Subject to change;
- Dynamic stability, pressure pulsation, uniform consistency.

OLD STUFF BOX



NEW STUFF BOX



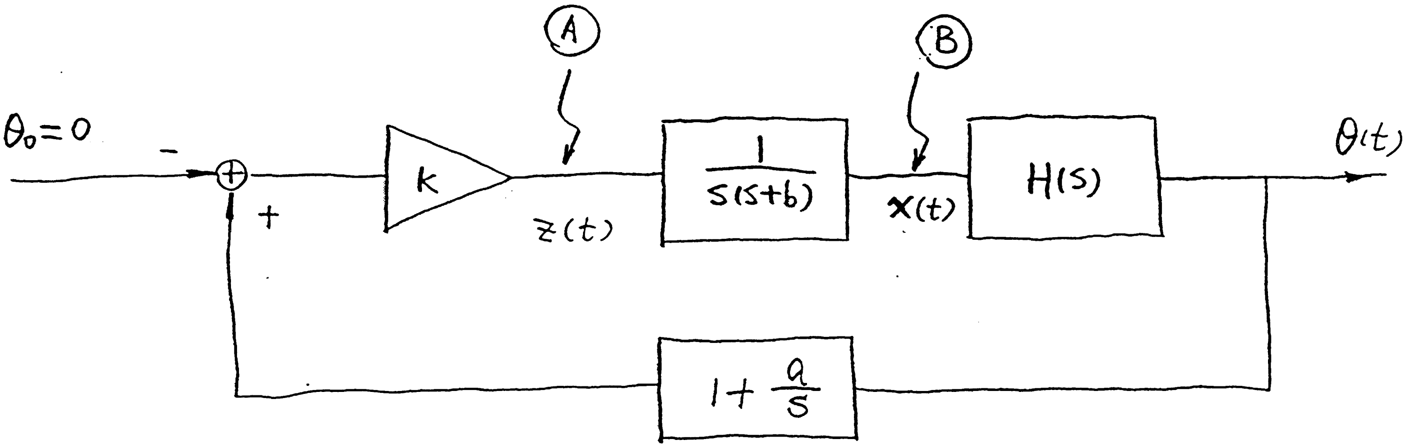
m – **Stick Mass**

$I_o = mr^2$ – **Moment of Inertia (about point O)**

$r = \sqrt{\alpha}\, l$ – **Radius of Gyration**

g – **Acceleration of Gravity**

To stable the system, the feedback control loop is used



$$\Delta\theta(t) = \theta(t) - \theta_o$$

At (A) $\quad z(t) = k\Delta\theta(t) + ka\int_0^t \theta(t)\,dt$

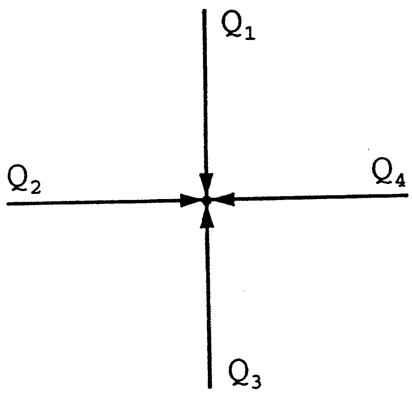
At (B) $\quad \ddot{x}(t) + b\dot{x}(t) = z(t)$

From (A) to (B), the signal $z(t)$, which carries the information about the deviation angle, is transformed into cart acceleration and velocity.

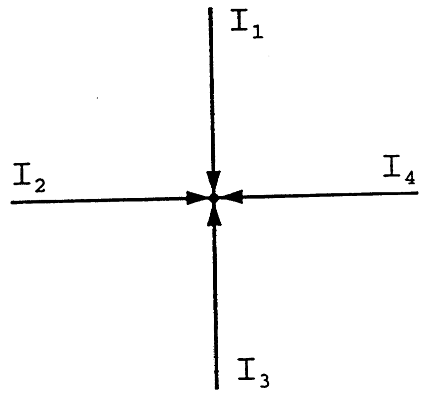
From $\quad I_o\ddot{\theta}(t) + ml\ddot{x}(t) - mgl\theta(t) = 0 \Rightarrow H(s) = \dfrac{-s^2}{\alpha l s^2 - g}$.

Computer Modeling

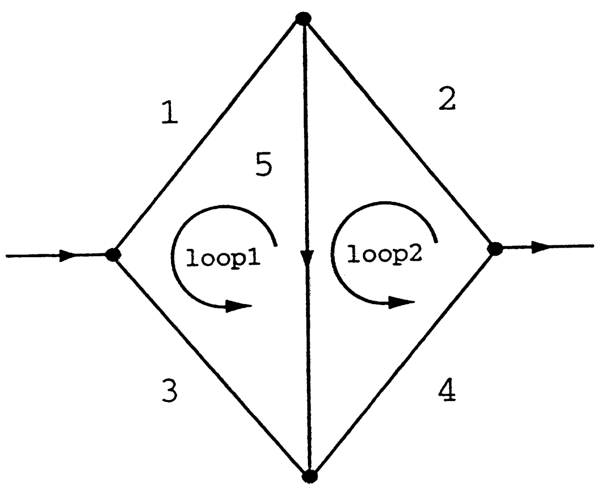
- Analogy to electrical circuits;
- Nonlinear dynamical behavior;
- Simulation softwares.



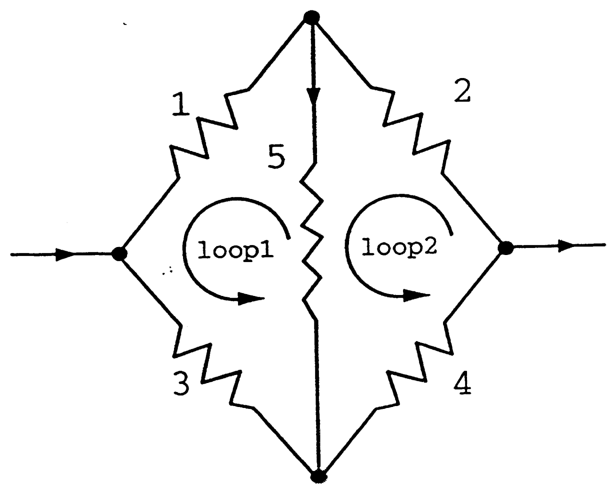
$$Q_1 + Q_2 + Q_3 + Q_4 = 0$$



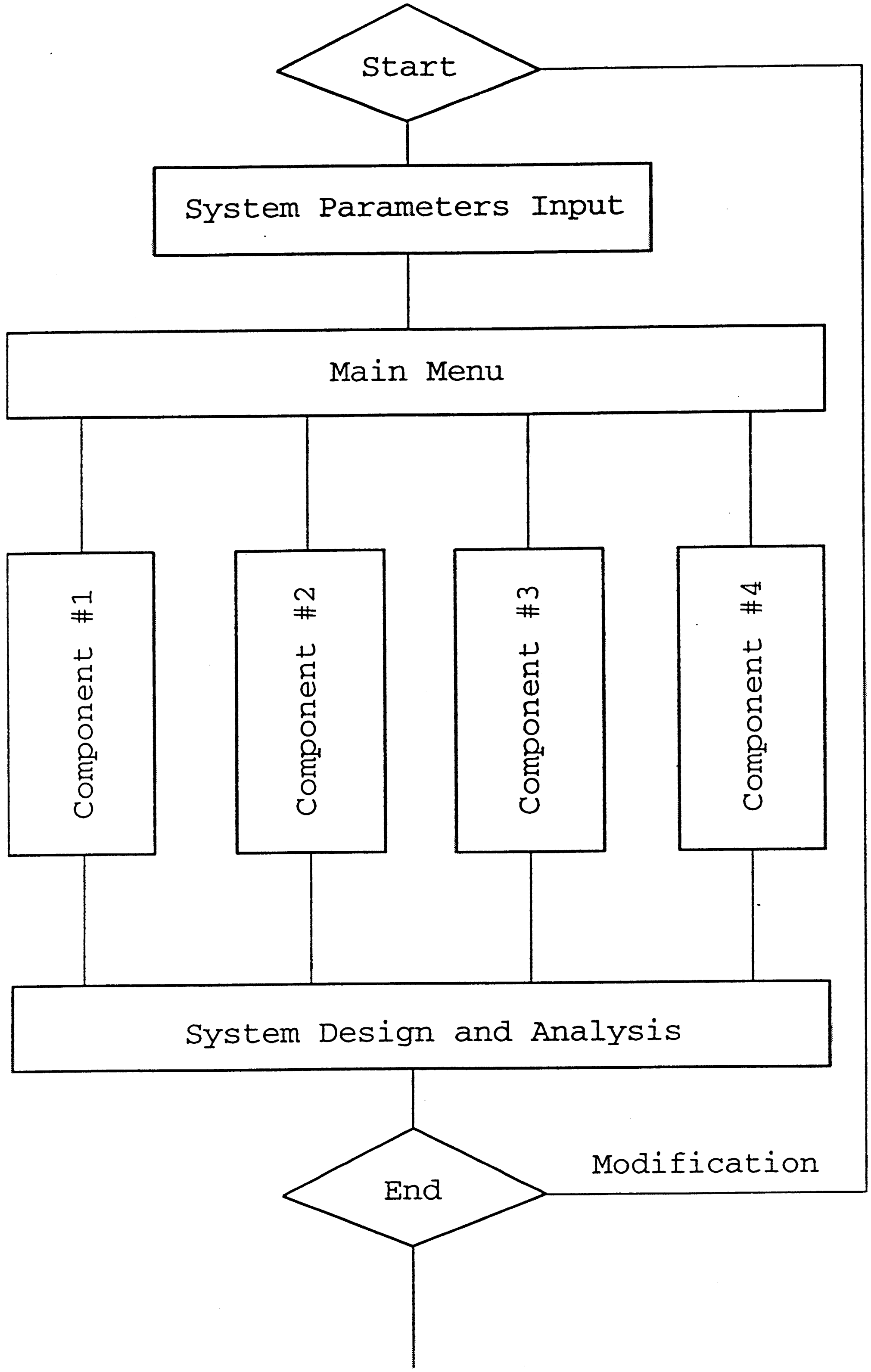
$$I_1 + I_2 + I_3 + I_4 = 0$$



$$\mathrm{D}H_1 + \mathrm{D}H_5 + \mathrm{D}H_3 = 0$$
$$\mathrm{D}H_2 + \mathrm{D}H_4 - \mathrm{D}H_5 = 0$$

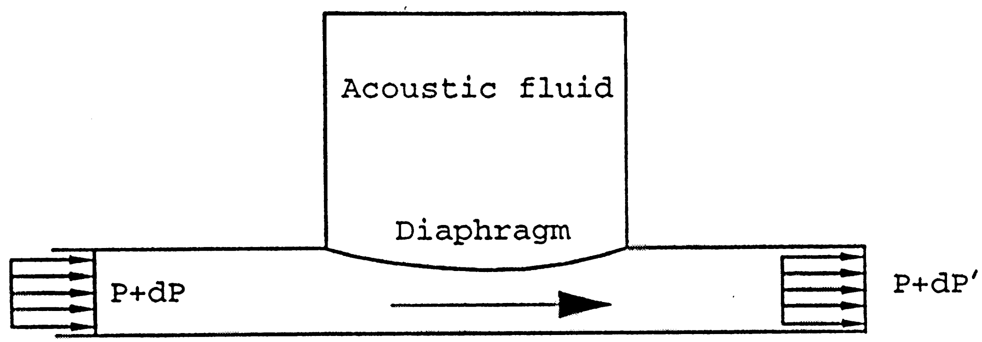


$$\mathrm{D}V_1 + \mathrm{D}V_5 + \mathrm{D}V_3 = 0$$
$$\mathrm{D}V_2 + \mathrm{D}V_4 - \mathrm{D}V_5 = 0$$


Start
System Parameters Input
Main Menu
Component #1
Component #2
Component #3
Component #4
System Design and Analysis
End
Modification

Pressure Pulsation Attenuator

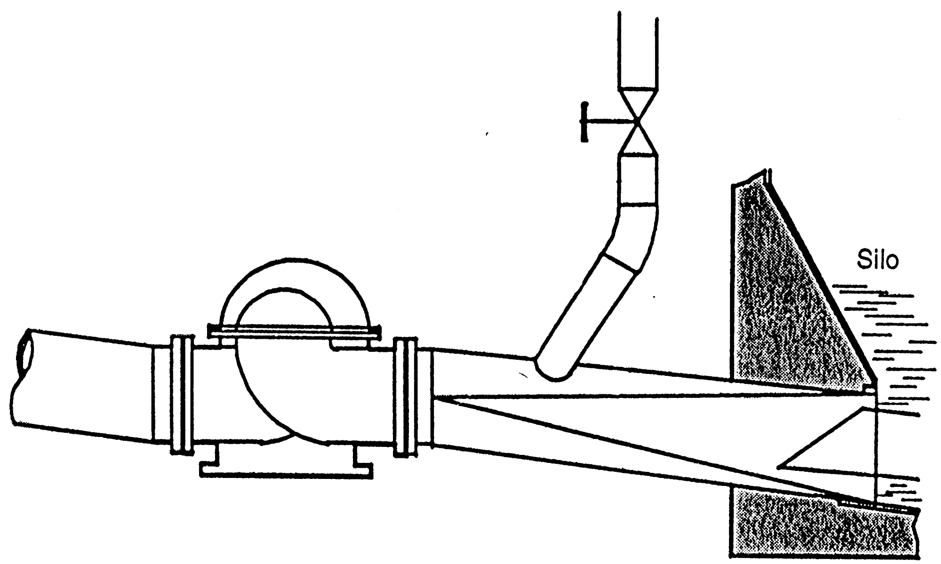
- Basis weight variations;
- Frequency range and attenuation gap;
- Computational tools to optimize the attenuator design.



Pressure pulsation attenuator mathematical model.

Mixing Before Fan Pump

- Turbulence effects;
- Relative pipe length;
- Computational model.



Conclusion

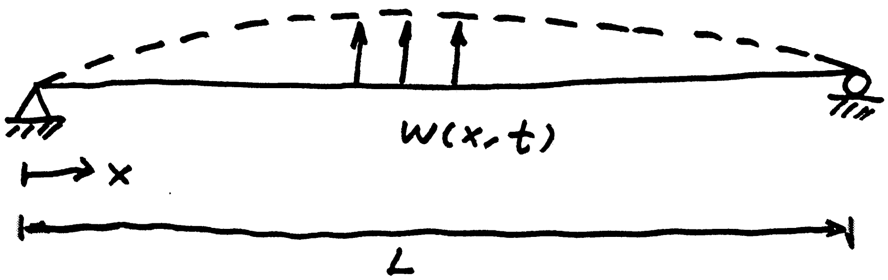
- Approach flow system project will be very promising;
- New former, high speed and smaller hydraulic headbox require the smooth and uniform delivery of stock from approach flow system;
- Potential to become one of the leading projects at IPST.

Air-Sheet Interaction Project

Xiaodong Wang, Assistant Professor
Institute of Paper Science and Technology

Objectives and Approaches

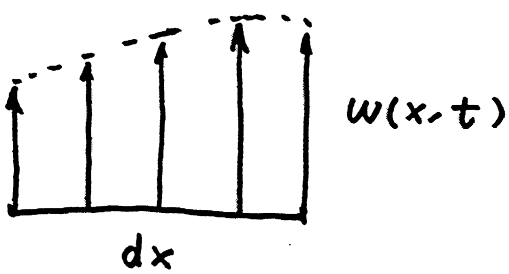
- Stabilize the sheet in open draws;
- Characterize the parameters;
- Develop flutter suppression devices.



total length increment in x : $\frac{1}{2}\int_0^L \left(\frac{\partial w}{\partial x}\right)^2 dx$

Take the differential element : dx

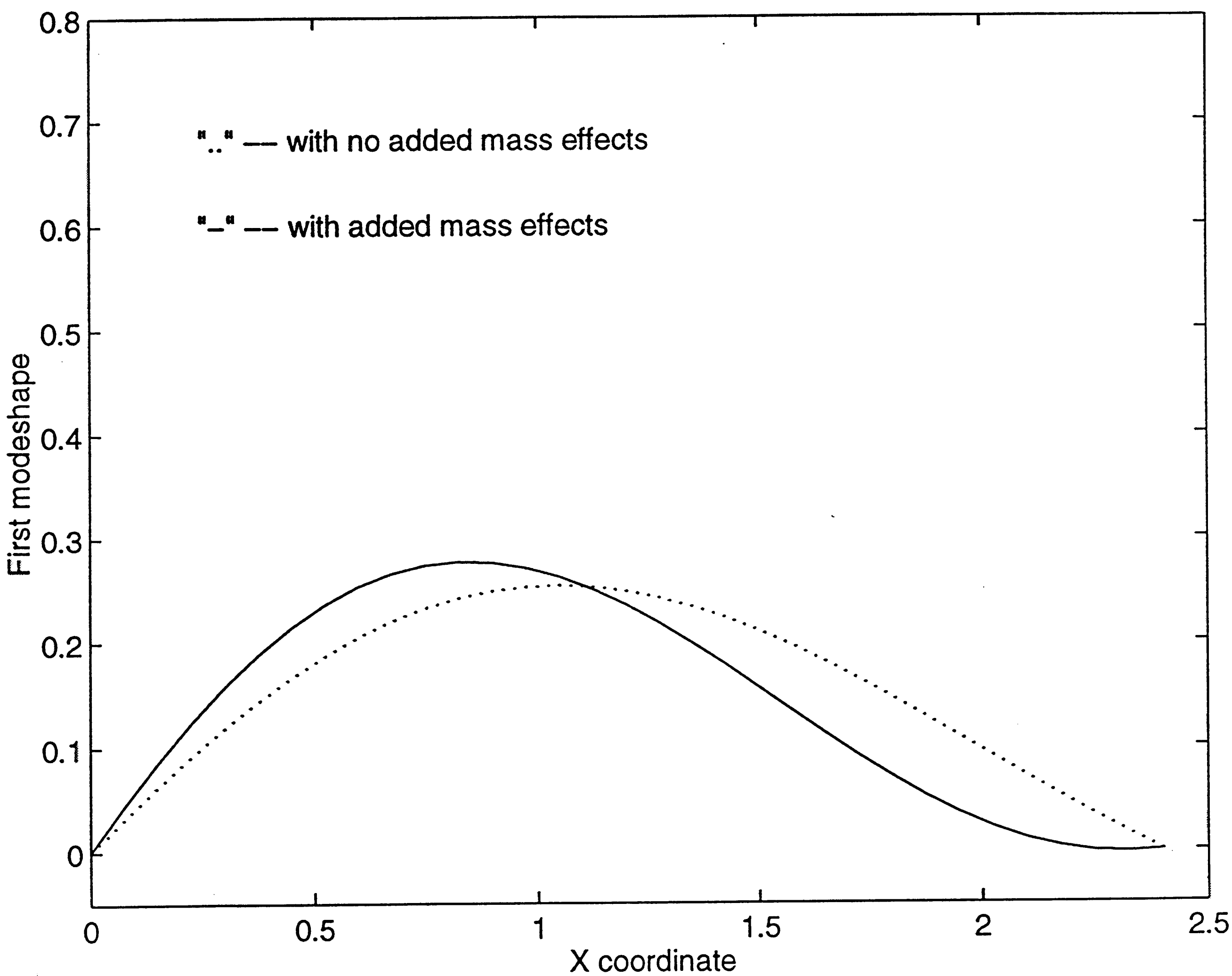
$$\sqrt{dx^2 + dw^2} = dx\sqrt{1 + \left(\frac{\partial w}{\partial x}\right)^2}$$



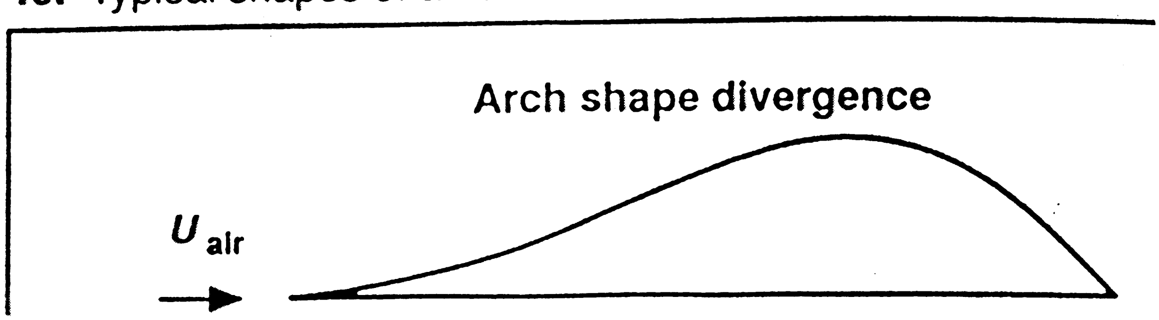
$$e_{xx} = \frac{\sqrt{dx^2 + dw^2} - dx}{dx} = \sqrt{1 + \left(\frac{\partial w}{\partial x}\right)^2} - 1$$

$$= \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2$$

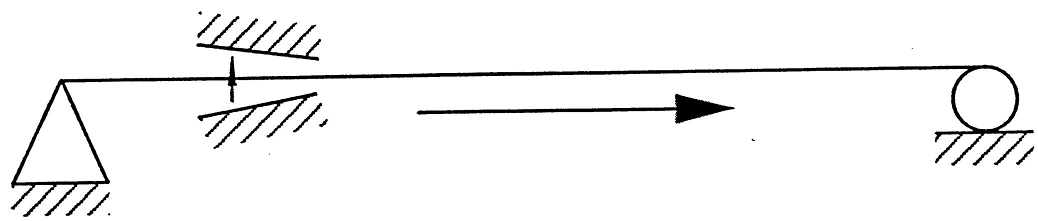
$$O(\epsilon^2)$$

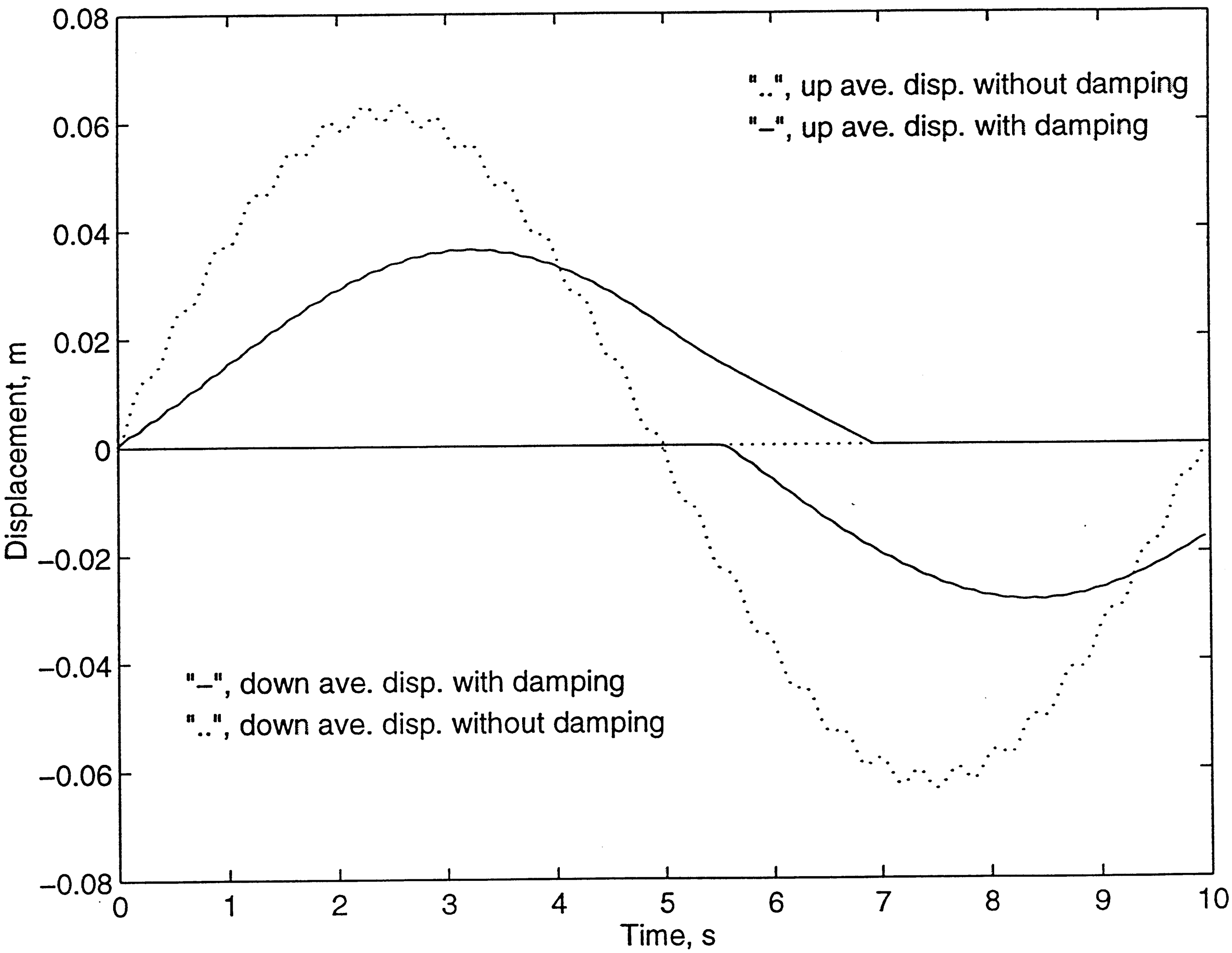


10. Typical shapes of an unstable web in a wind

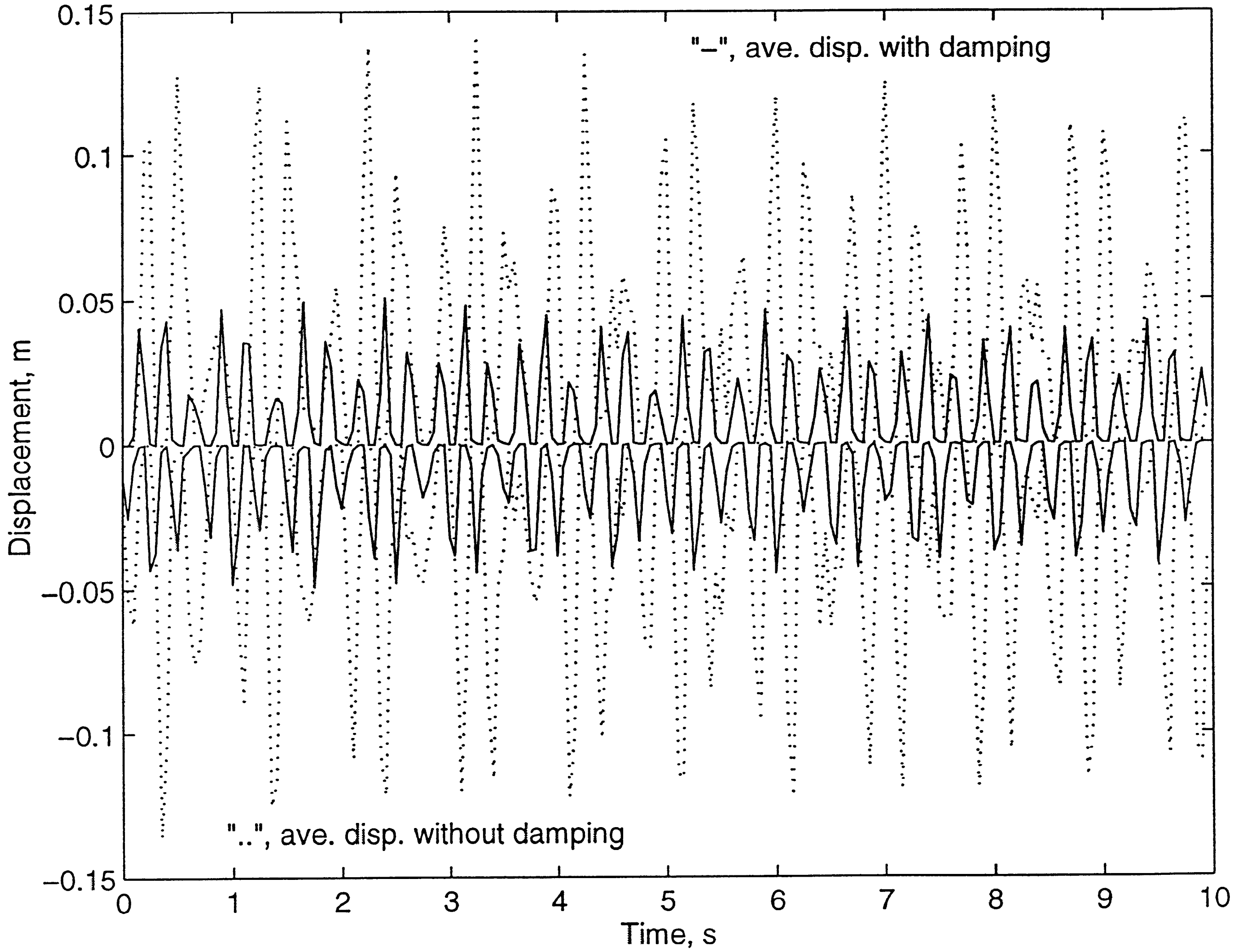


Two-sided suppression device





"..", up ave. disp. without damping
"–", up ave. disp. with damping
"–", down ave. disp. with damping
"..", down ave. disp. without damping
Displacement, m
Time, s
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
0
1
2
3
4
5
6
7
8
9
10



"–", ave. disp. with damping
"..", ave. disp. without damping
Displacement, m
Time, s
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
0
1
2
3
4
5
6
7
8
9
10

Future Planning

- Experimental confirmation;
- Mill implementation.

Conclusion and Discussion

- focus on reducing the out-of-plane displacement;
- design the suppression device to achieve the active damping;
- look into the Navier-Stokes equations and include the turbulence effects;
- study the nonlinear dynamic aspects including different excitation forces.