THERMAL TRANSPORT IN HIGH SPEED OPTICAL FIBER DRAWING AND COATING

YOGESH JALURIA

Department of Mechanical and Aerospace Engineering

Rutgers, the State University of New Jersey

New Brunswick, NJ 08903

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Outline

- Thermal Processing of Materials
- Manufacture of Optical Fibers
- Furnace Optical Fiber Drawing
- Thermally Induced Defects
- Process Feasibility
- Fiber Cooling
- Coating of Fibers
- Furnace Wall Temperature Measurement
- Design and Optimization
- Conclusions and Future Research Needs

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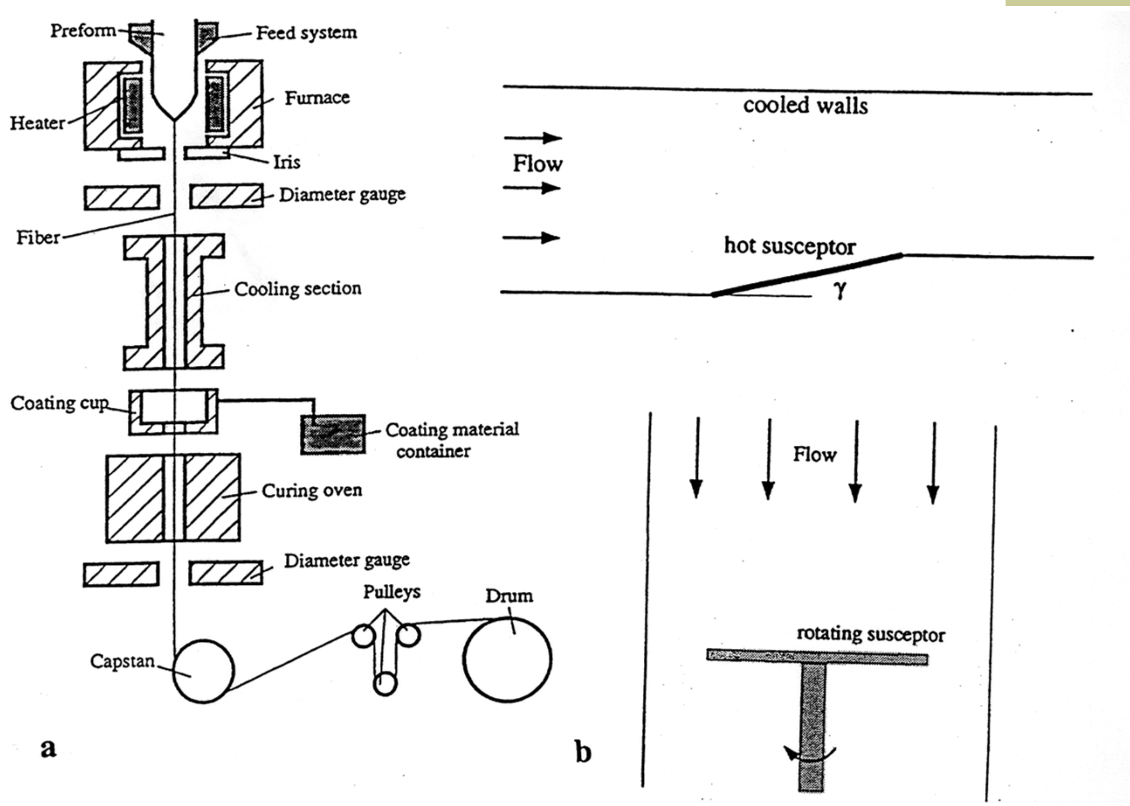
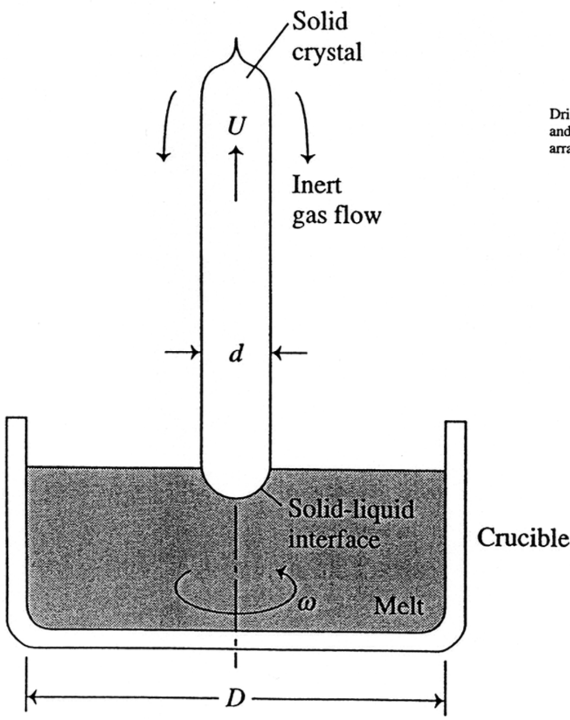
Thermal Processing of Materials

Optical Fiber Drawing and Chemical Vapor Deposition



Czochralski Crystal Growing and Polymer Screw Extrusion



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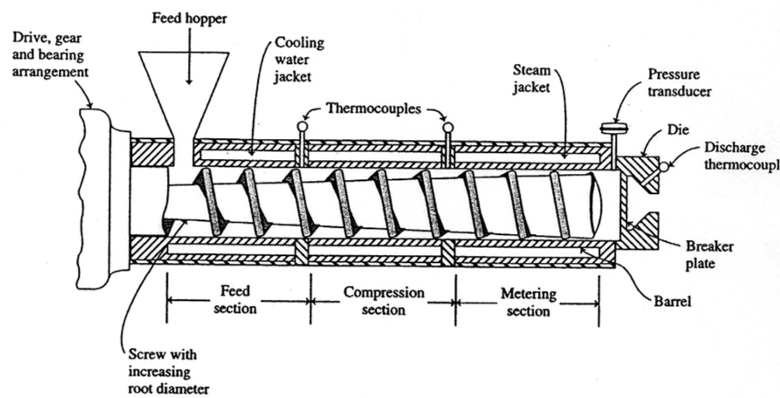

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Different Thermal Materials Processing Operations

1. PROCESSES WITH PHASE CHANGE
   casting, continuous casting, crystal growing, drying
2. HEAT TREATMENT
   annealing, hardening, tempering, surface treatment, curing, baking
3. FORMING OPERATIONS
   hot rolling, wire drawing, metal forming, extrusion, forging
4. CUTTING
   laser and gas cutting, fluid jet cutting, grinding, machining
5. BONDING PROCESSES
   soldering, welding, explosive bonding, chemical bonding
6. POLYMER PROCESSING
   extrusion, injection molding, thermoforming

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Different Thermal Materials Processing Operations (Contd.)

7. REACTIVE PROCESSING

chemical vapor deposition, food processing

8. POWDER PROCESSING

powder metallurgy, sintering, sputtering, processing of nano-powders and ceramics

9. GLASS PROCESSING

optical fiber drawing, glass blowing, annealing

10. COATING

thermal spray coating, polymer coating

11. OTHER PROCESSES

composite materials processing, microgravity materials processing, rapid prototyping

Important Basic Considerations

- **COUPLING OF TRANSPORT WITH MATERIAL CHARACTERISTICS**
  different materials, properties, behavior, material structure
- **VARIABLE MATERIAL PROPERTIES**
  strong variation with temperature, pressure and concentration
- **COMPLEX GEOMETRIES**
  complicated domains, multiple regions
- **COMPLICATED BOUNDARY CONDITIONS**
  conjugate conditions, combined modes
- **INTERACTION BETWEEN DIFFERENT MECHANISMS**
  surface tension, heat and mass transfer, chemical reactions, phase change
- **MICRO-MACRO COUPLING**
  micro-structure changes, mechanisms operating at different length and time scales
- **COMPLEX FLOWS**
  non-Newtonian flows, free surface flows, powder and particle transport

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Important Engineering Aspects

- PROCESS FEASIBILITY
- DESIGN OF RELEVANT THERMAL SYSTEM
- SYSTEM OPTIMIZATION AND CONTROL
- PRODUCT CHARACTERISTICS
- PRODUCT DEVELOPMENT
- INVERSE PROBLEMS
- DIFFERENT ENERGY SOURCES
- PRODUCTIVITY, COST

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Manufacture of Optical Fibers

Optical Fiber Drawing System

- Drawing Furnace
- Fiber Cooling
- Coating
- Curing
- Take-Up

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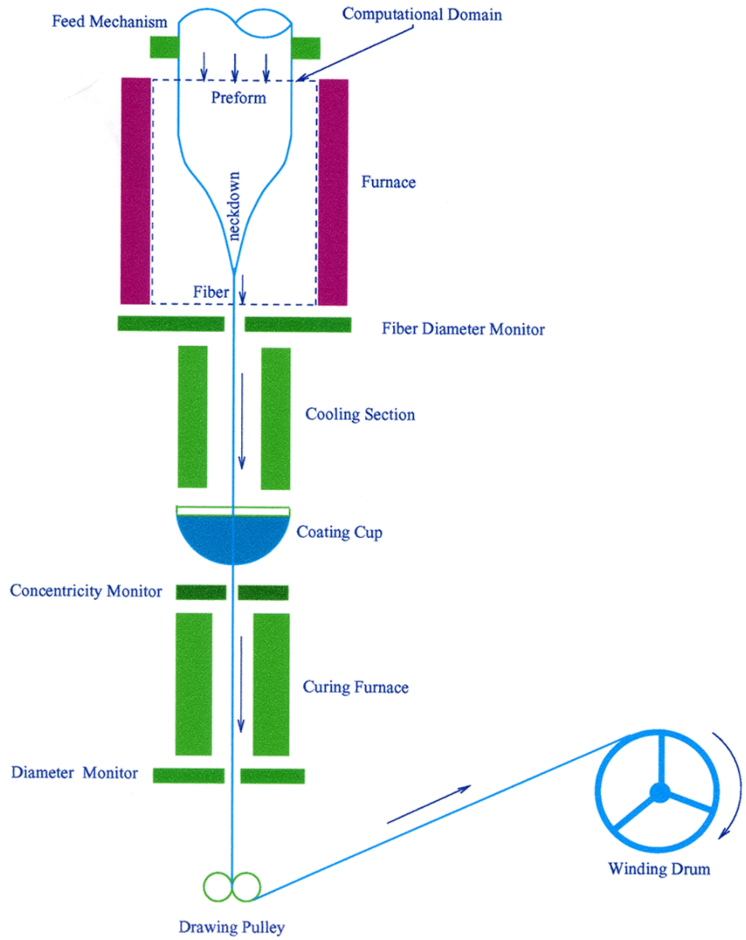
Sketch of Optical Fiber Drawing System



Furnace Drawing of Optical Fibers

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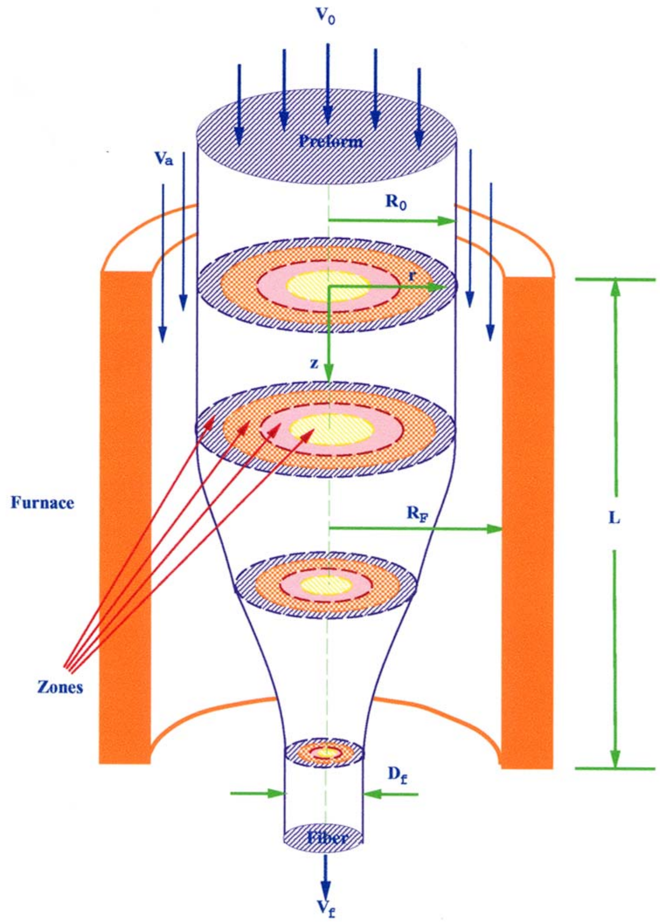
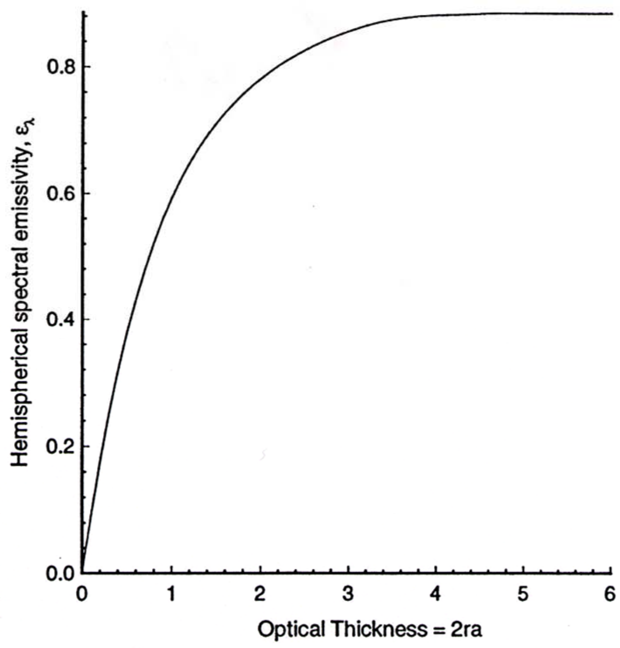
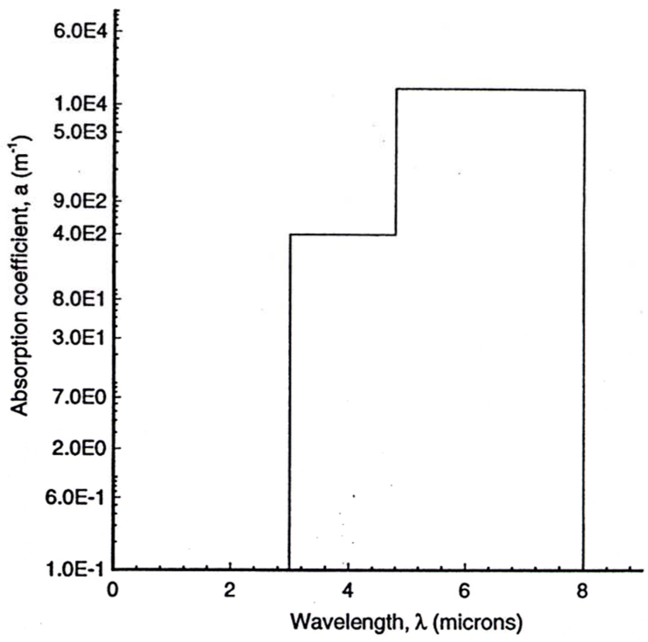
Cylindrical Draw Furnace and Finite Zones For Radiation Analysis

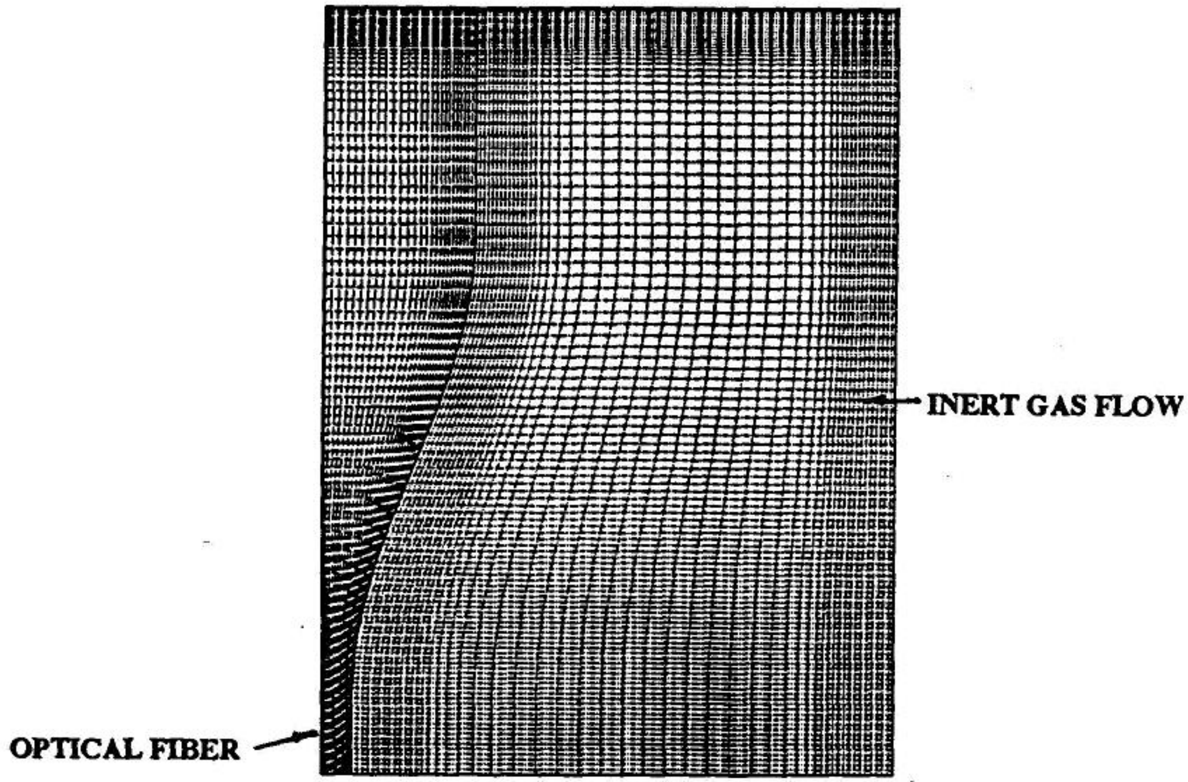


Material properties: Radiation Properties of Silica Glass





Grid for Numerical Modeling of Flow in Optical Fiber Drawing



Governing Equations

$$\frac{\partial v}{\partial z} + \frac{1}{r}\frac{\partial (ru)}{\partial r} = 0$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}\left[r\,\nu \left(\frac{\partial v}{\partial r} + \frac{\partial u}{\partial z}\right)\right] + 2\frac{\partial}{\partial z}\left(\nu\frac{\partial v}{\partial z}\right)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{2}{r}\frac{\partial}{\partial r}\left(r\,\nu\frac{\partial u}{\partial r}\right) + \frac{\partial}{\partial z}\left[\nu\left(\frac{\partial v}{\partial r} + \frac{\partial u}{\partial z}\right)\right] - \frac{2\nu u}{r^2}$$

$$\rho\, C_p \left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial r} + v\frac{\partial T}{\partial z}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\,K\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + \Phi + S_r$$

where Φ is the viscous dissipation and is given by

$$\Phi = \mu\left\{2\left[\left(\frac{\partial u}{\partial r}\right)^2 + \left(\frac{u}{r}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r}\right)^2\right\}$$

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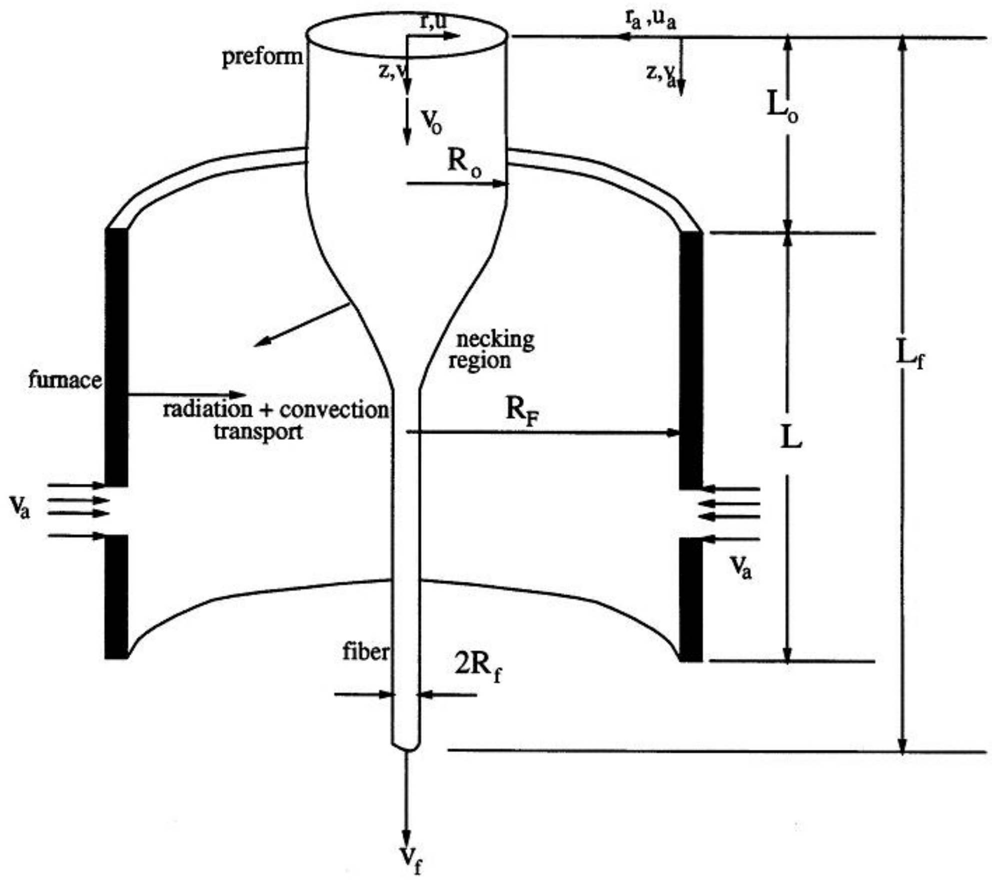
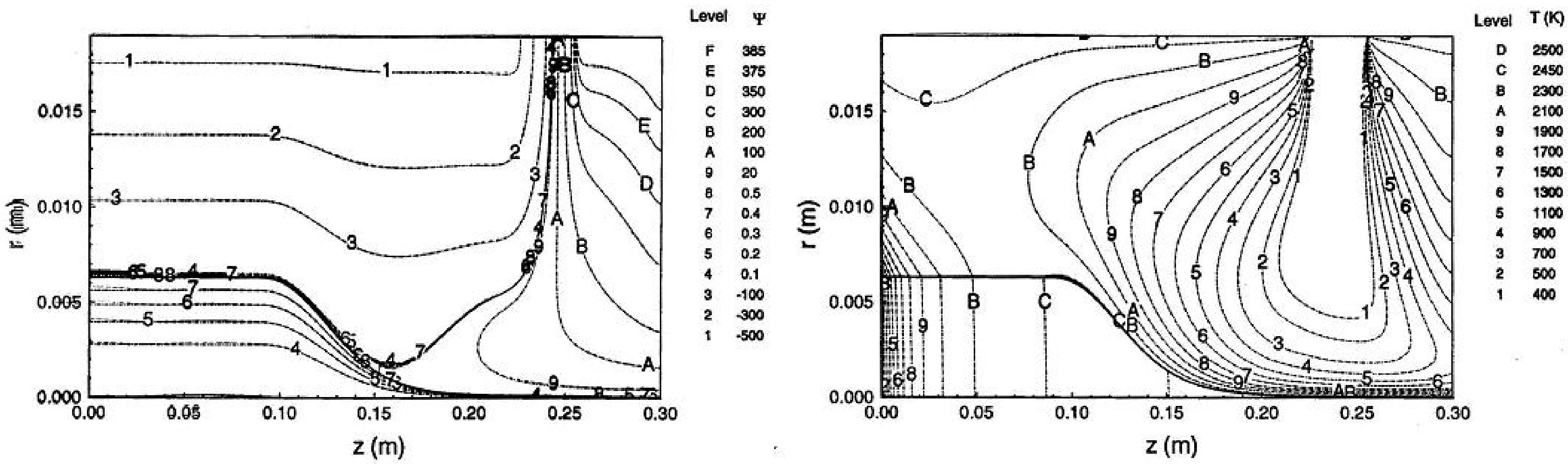
Schematic Diagram of the Thermal Transport Process for Furnace Drawing of an Optical Fiber, Using Peripheral Flow



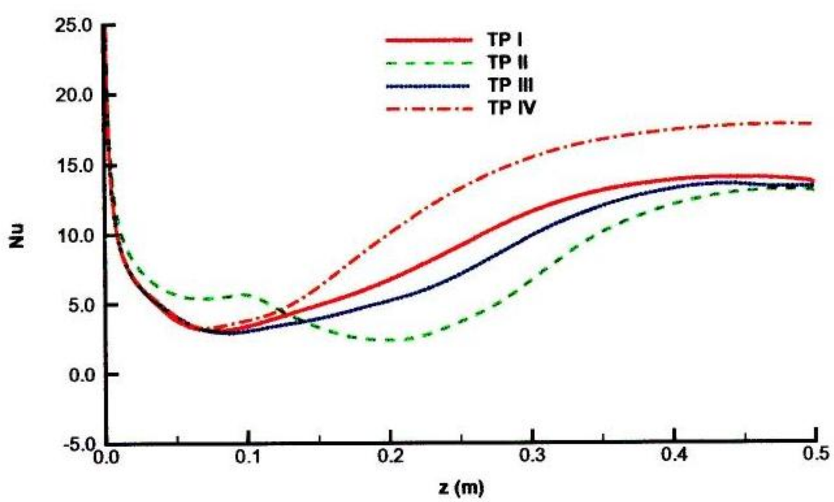
Inert Gas Flow in Optical Fiber Drawing Furnace



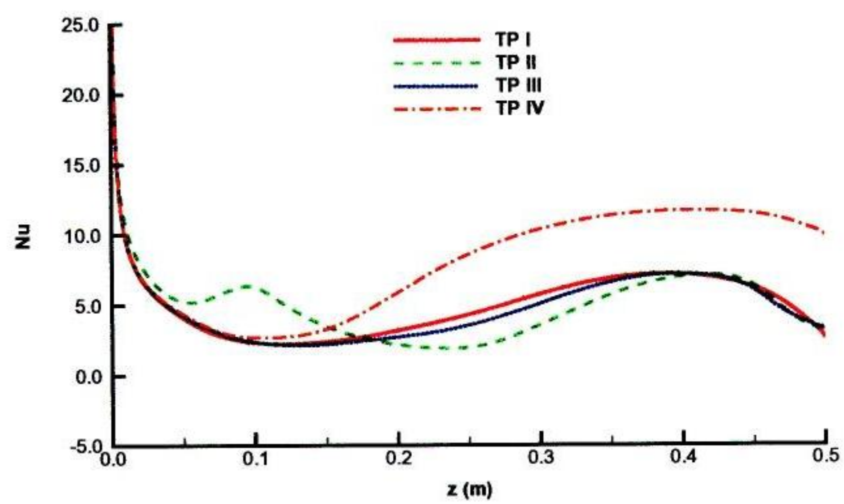
(a) Streamlines

(b) Isotherms

Nusselt Number Variation



(I) L = 50 cm , V_f = 5 m/s



(II) L = 50 cm , V_f = 15 m/s

TPI, II, .. Represent Different Furnace Wall and Preform Temperature Distributions

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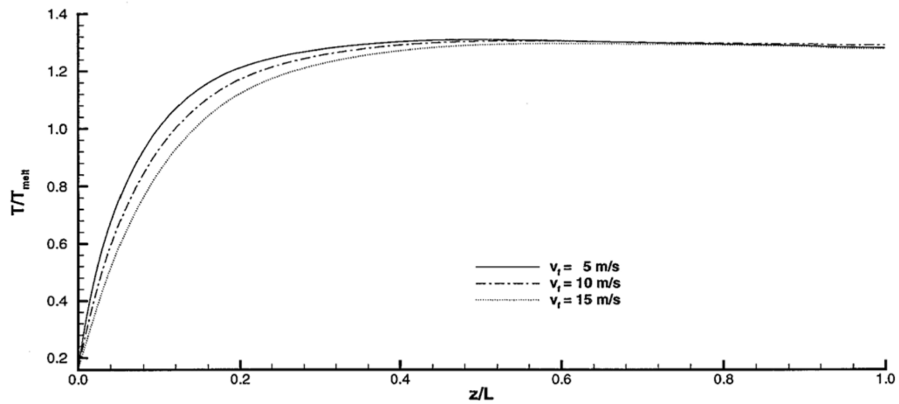
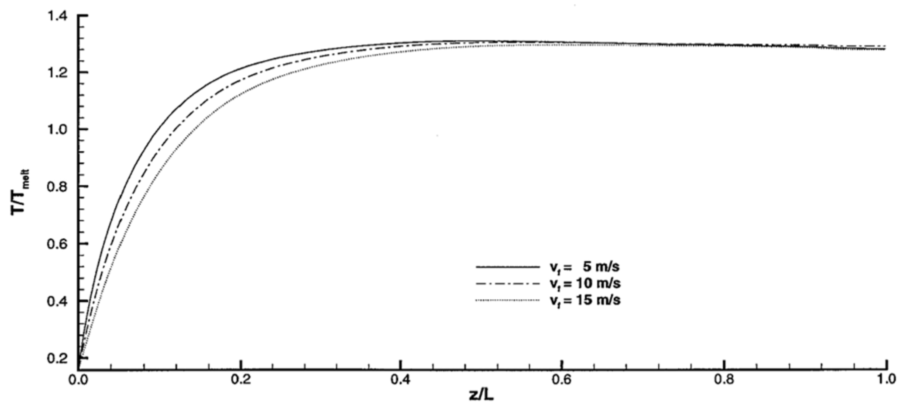
Preform Temperature Distributions for Different Fiber Drawing Speeds

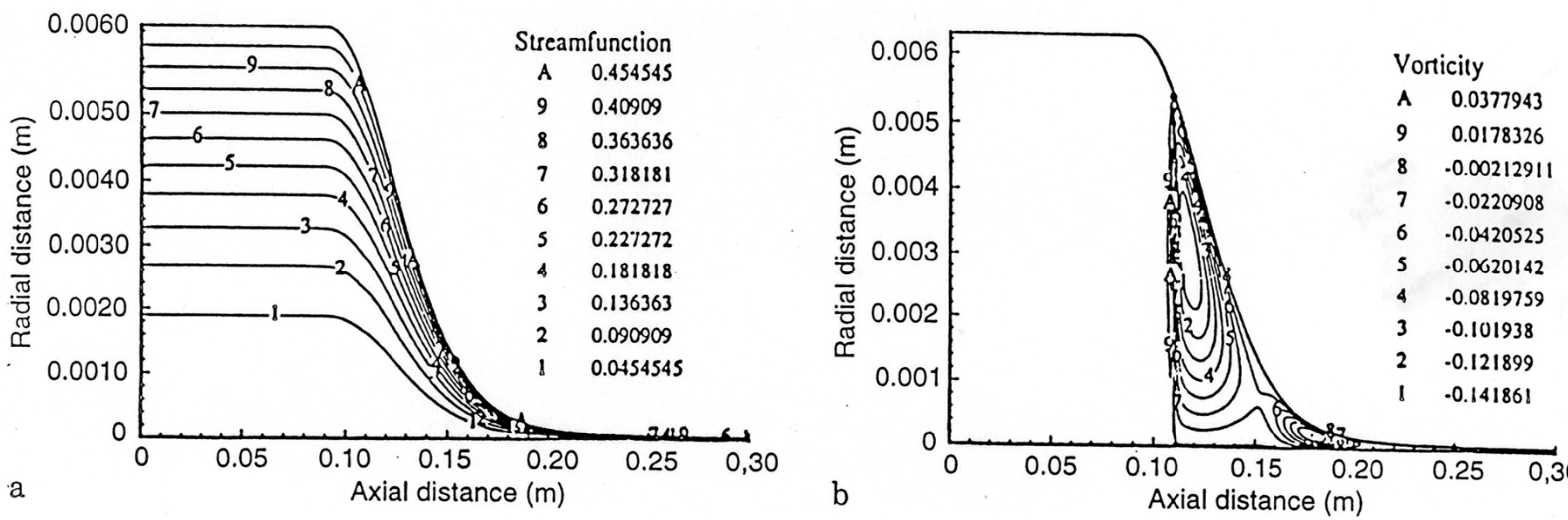


(a) Centerline temperature

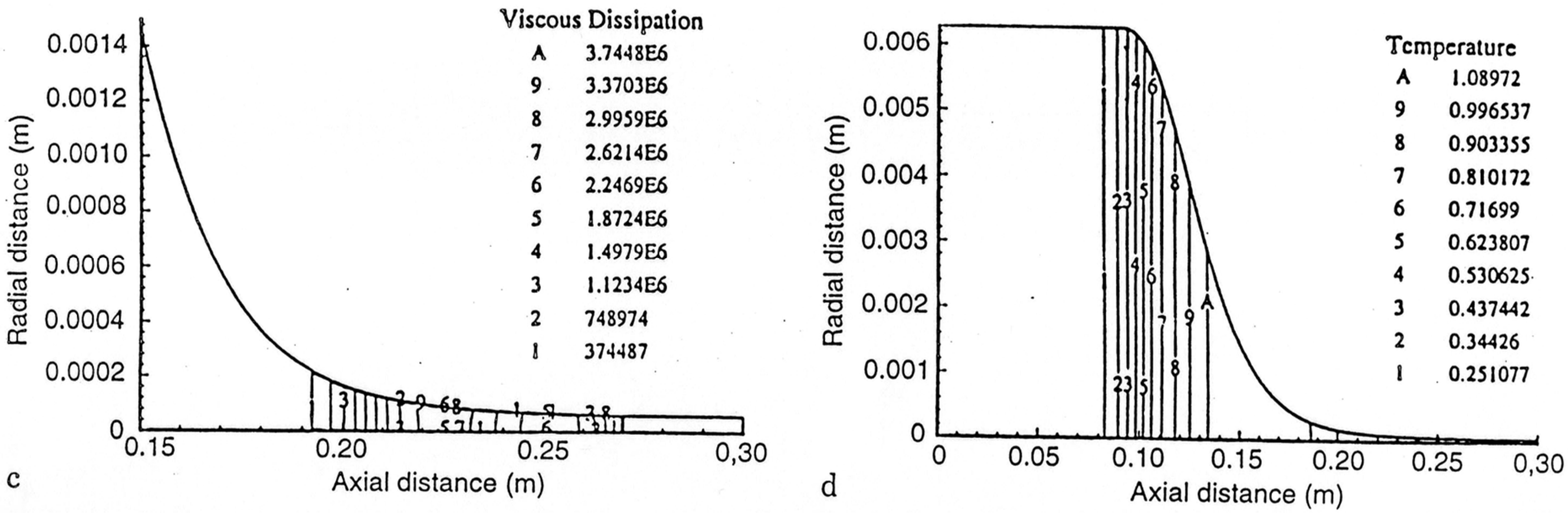


(b) Surface temperature

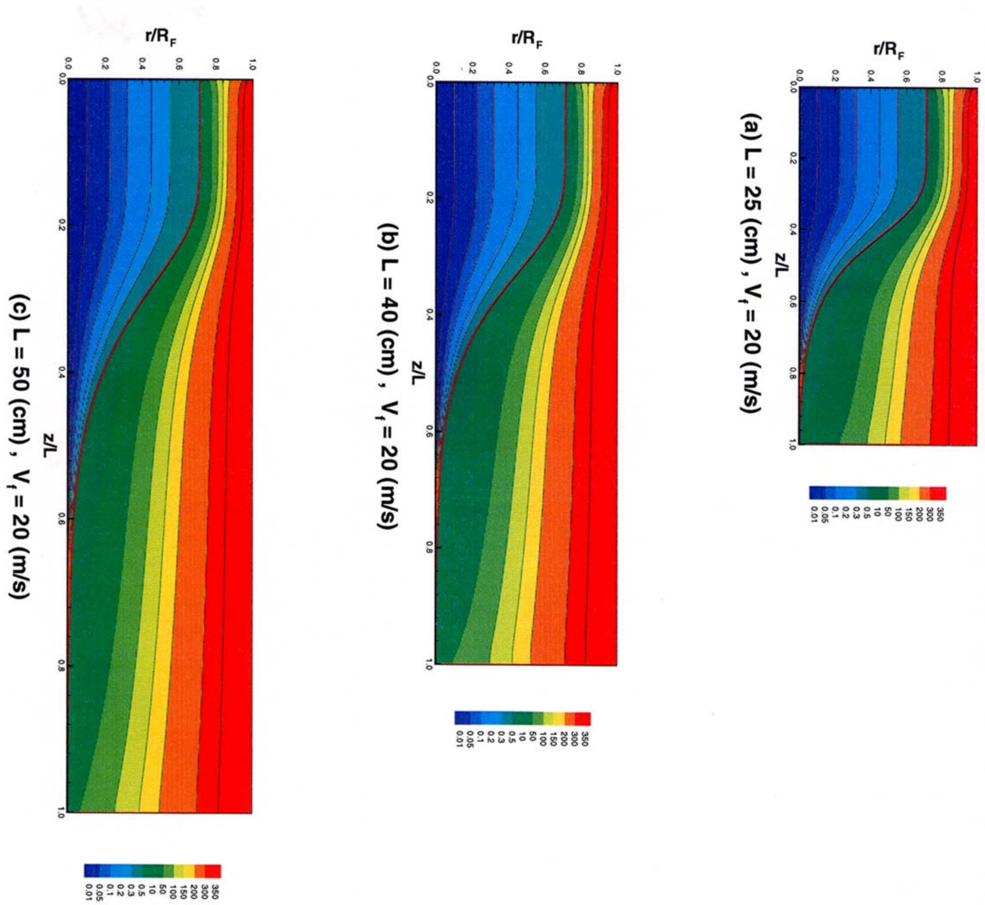
Flow in Neck-Down Region During Optical Fiber Drawing



Flow in Neck-Down Region During Optical Fiber Drawing



Streamlines in Optical Fiber Drawing



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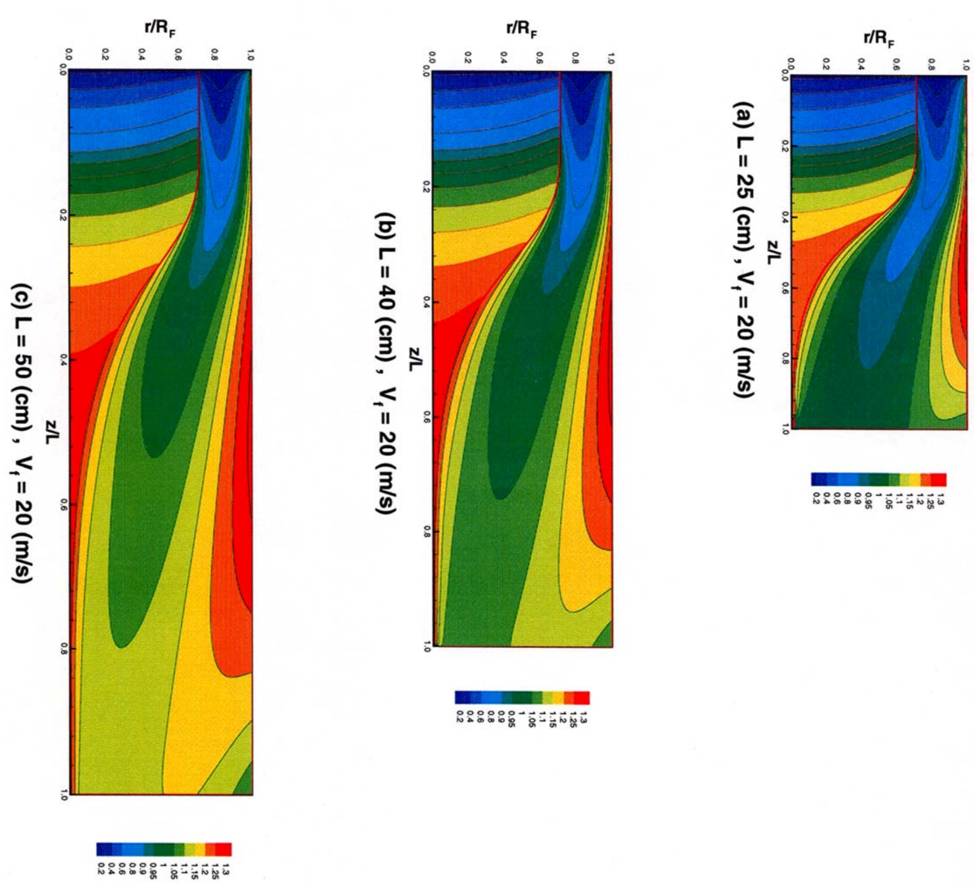
Isotherms in Optical Fiber Drawing



Neck-Down Profile

Force Balances on Free Surface

$$R(z) = \sqrt{\frac{R_0^2 v_0}{\bar{v}}}$$

where $\bar{v}$ is the average axial velocity in the glass, which is given as

$$\bar{v} = C_1 \int_0^x \frac{dz}{\mu R^2} - \int_0^x \frac{\rho g}{C_2 \mu R^2} \left(\int_0^x R^2 dz\right) dz - \int_0^x \frac{1}{C_2 \mu R^2} \left[\int_0^x \zeta \left(\frac{R}{\sqrt{1 + R'^2}} + \frac{1}{R_1}\right) dz\right] dz$$

$$- 2 \rho R^4 v_0^2 \int_0^x \frac{1}{C_2 \mu R^2} \left(\int_0^x \frac{R'}{R^3} dz\right) dz$$

where, C_1, C_2 and R_1, the curvature, are defined as

$$C_1 = v_f - v_0 + \int_0^L \frac{\rho g}{C_2 \mu R^2} \left(\int_0^x R^2 dz\right) dz + \int_0^L \frac{1}{C_2 \mu R^2} \left[\left(\int_0^x \zeta \left(\frac{R}{\sqrt{1 + R'^2}} + \frac{1}{R_1}\right) dz\right] dz$$

$$+ 2 \rho R^4 v_0^2 \int_0^L \frac{1}{C_2 \mu R^2} \left(\int_0^x \frac{R'}{R^3} dz\right) dz$$

$$C_2 = 2 + \frac{1 - 2 R'^2 + 2 R' - R R''}{1 + R'^2}$$

$$R_1 = \frac{R''}{[1 + (R')^2]^{3/2}}$$

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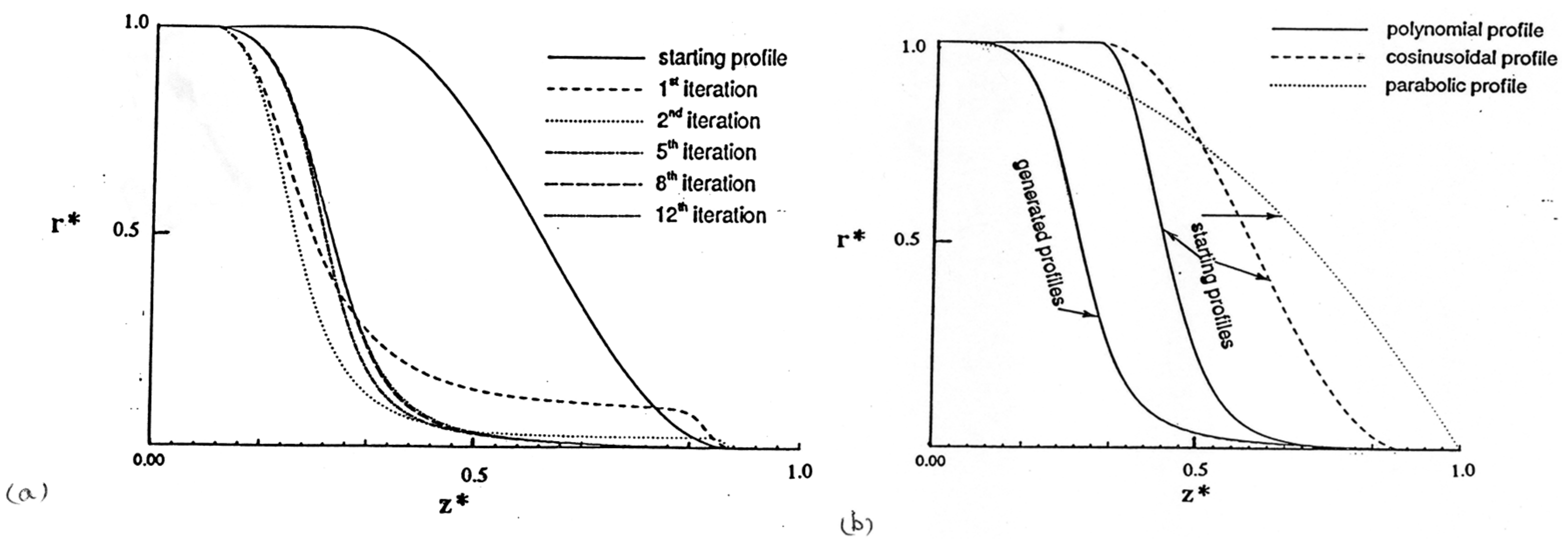
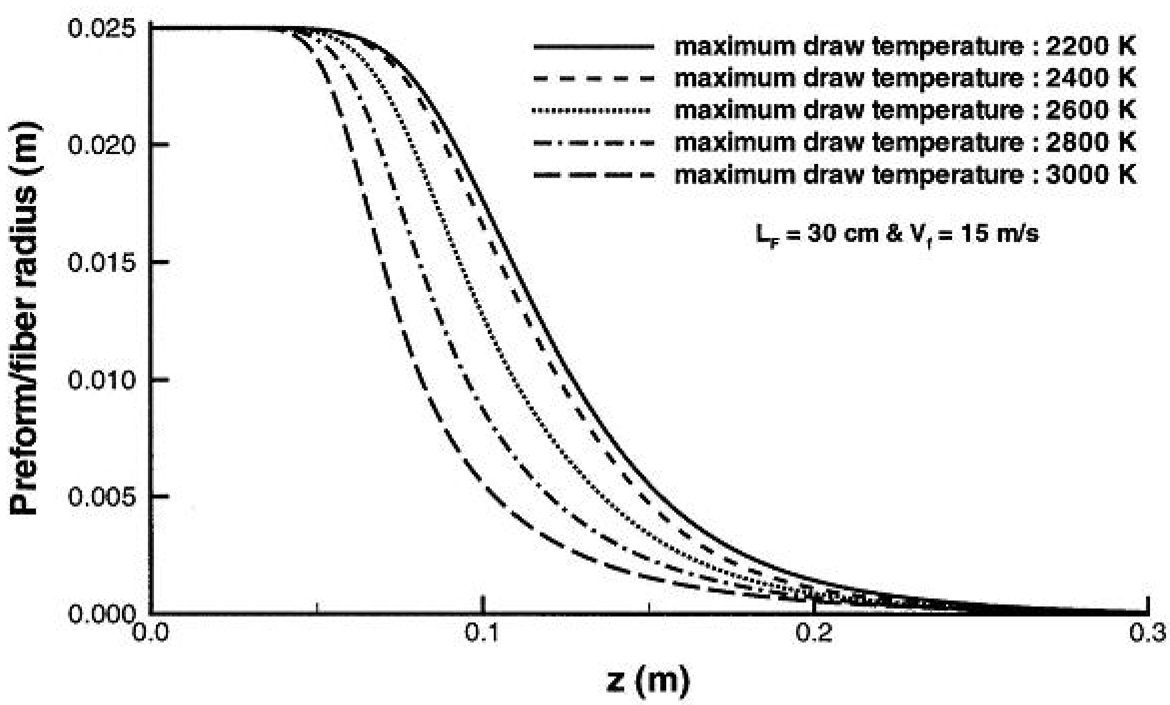
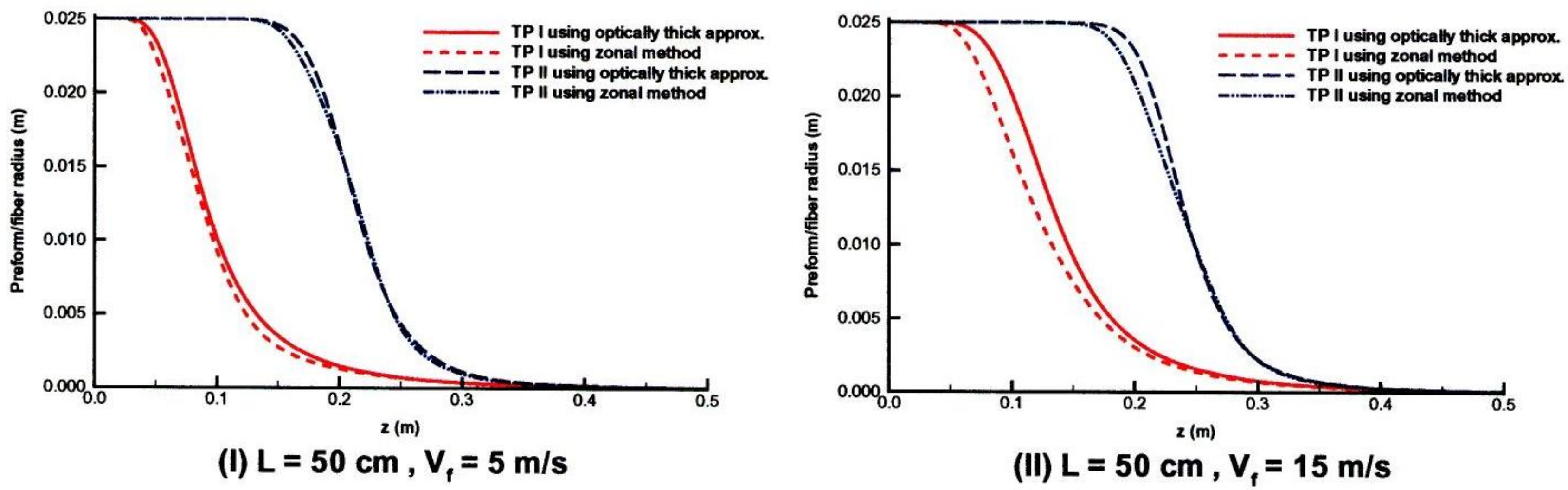
Generation of Neck-Down Profile



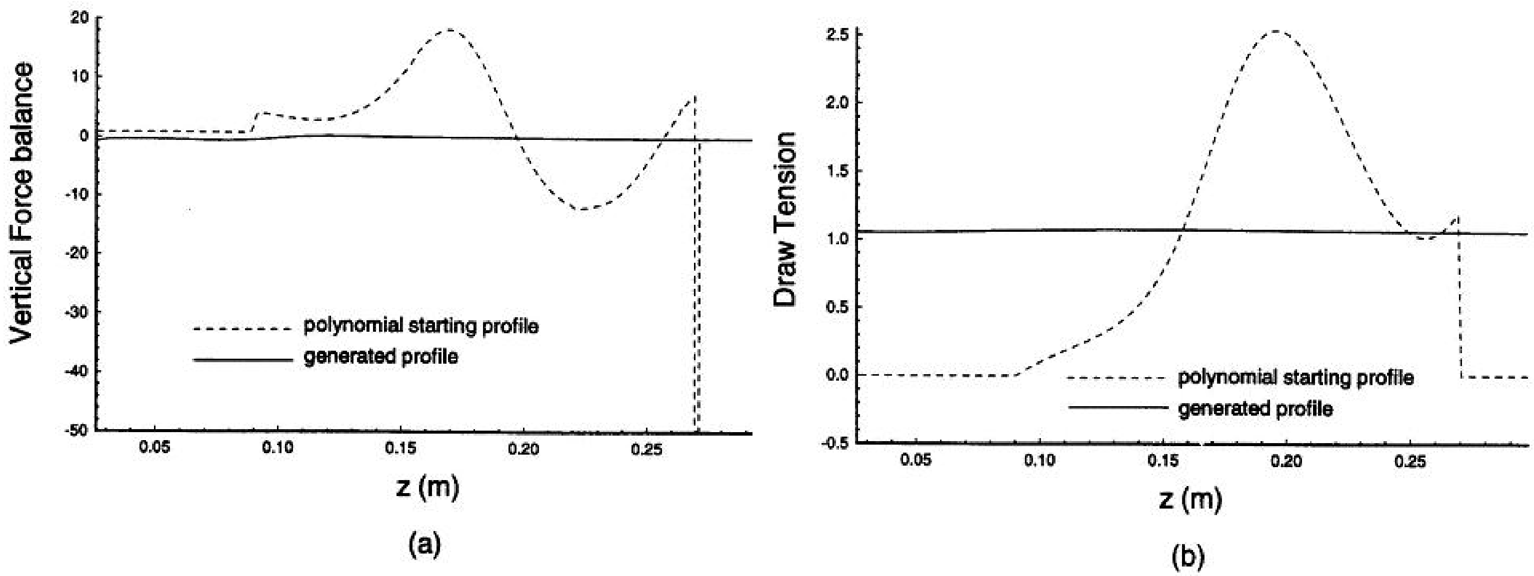
Neck-Down Profiles for Different Furnace Wall Temperatures



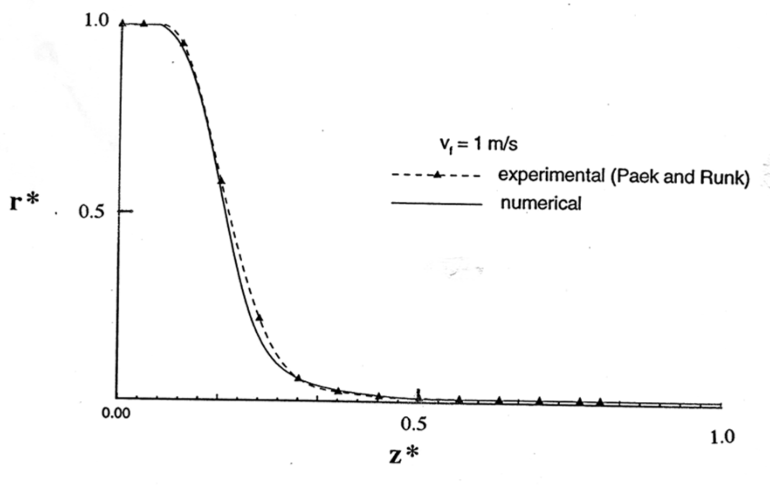
Neck-down Shapes Obtained by Optically Thick Approximation and by the Zonal Method



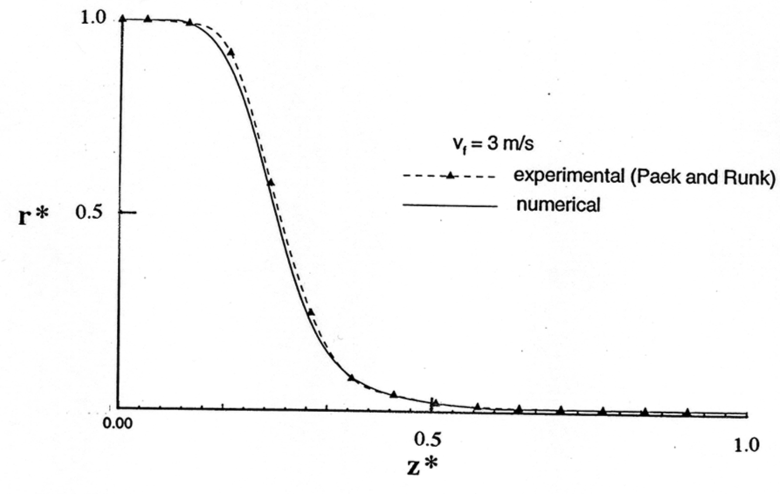
Vertical and Horizontal Force Balances During Profile Convergence



Neck-Down Profile from Numerical Simulation and Experimentation



(a)



(b)

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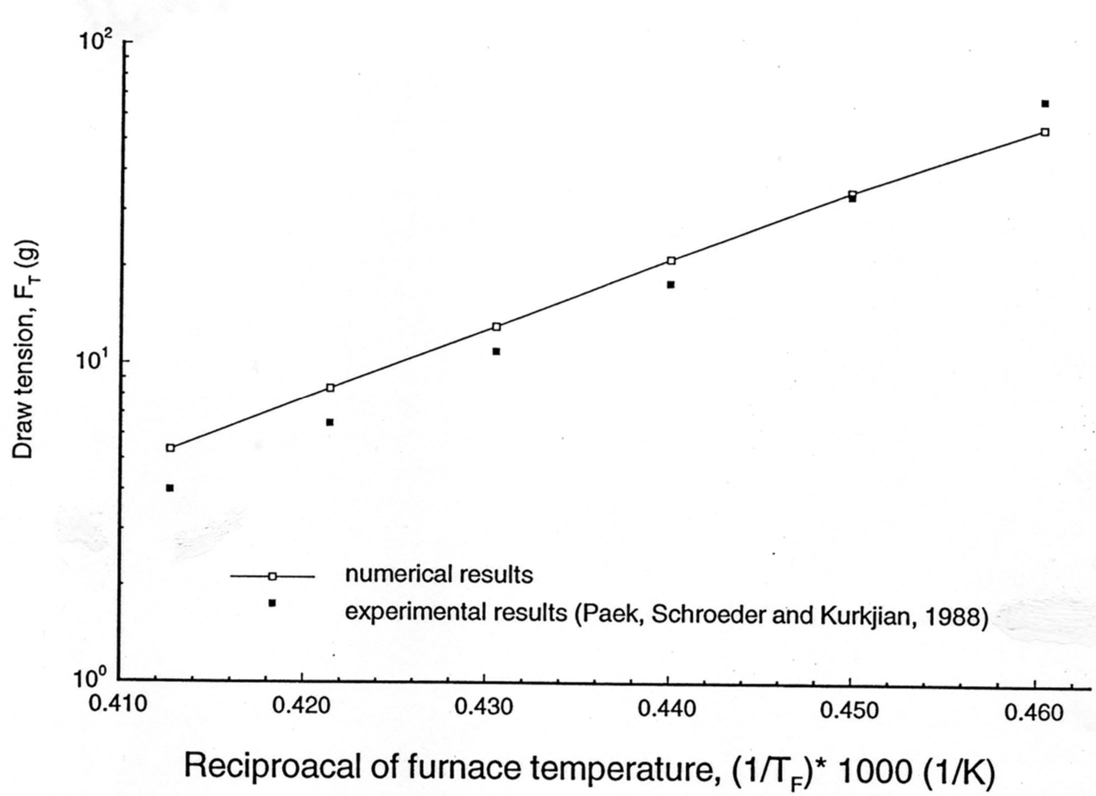
Calculated Versus Measured Tension in Optical Fiber Drawing



Thermally Induced Defects

E' Defect Generation

$$\frac{dn_d}{dt} = n_p \nu \exp\left(-\frac{E_p}{kT}\right) - n_d \nu \exp\left(-\frac{E_d}{kT}\right)$$

$$v \frac{dn_d}{dz} = n_p \nu \exp\left(-\frac{E_p}{kT}\right) - n_d \nu \exp\left(-\frac{E_d}{kT}\right)$$

$$n_d = n_p(0) - n_p$$

$$v \frac{dn_d}{dz} = n_p(0) \nu \exp\left(-\frac{E_p}{kT}\right) - n_d \nu \left[\exp\left(-\frac{E_p}{kT}\right) + \exp\left(-\frac{E_d}{kT}\right)\right]$$

The boundary condition for this equation is given by

$$n_d(0) = 0$$

where E_p=6.4087 x 10^{-19} J, E_d =0.3204 x 10^{-19} J, ν =8 x 10^{-3} s^{-1}, and $n_p(0)$ =7 x 10^{22} g^{-1}.

If the preform is assumed to be in an equilibrium state at temperature T_{melt},

$$\frac{dn_d}{dt} = 0$$

Therefore, from the preceding equations, the defect concentration in the equilibrium state at T_{melt} is obtained as

$$n_d(T_{melt}) = \frac{n_p(0) \exp\left(-\frac{E_p}{kT}\right)}{\exp\left(-\frac{E_p}{kT}\right) + \exp\left(-\frac{E_d}{kT}\right)}$$

At T_{melt}=1900K, the value of $n_d(T_{melt})$ is 1.832 x 10^{12} g^{-1}.

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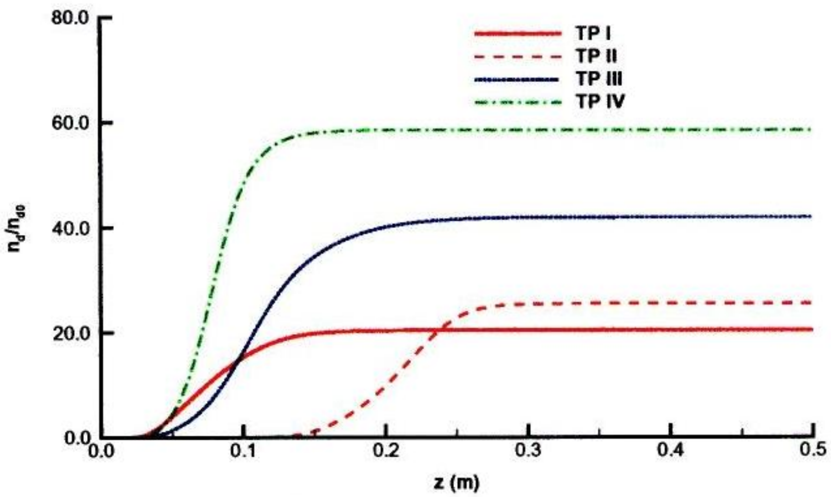
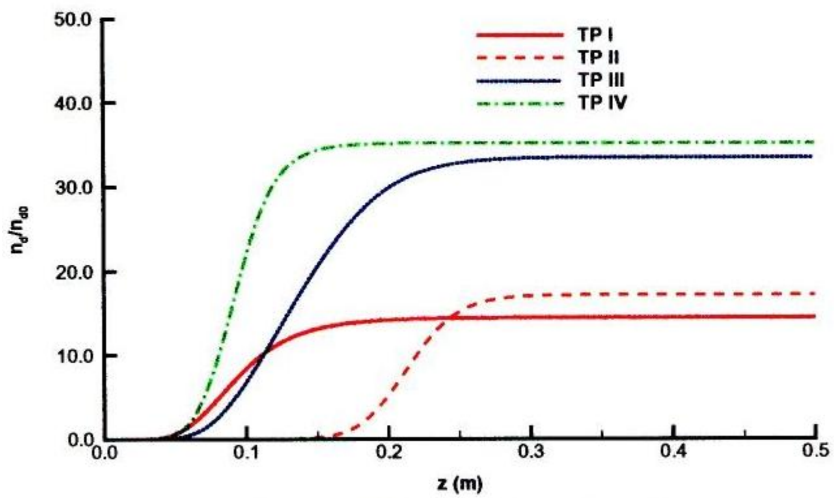
Downstream Variation of Thermally Induced Defects

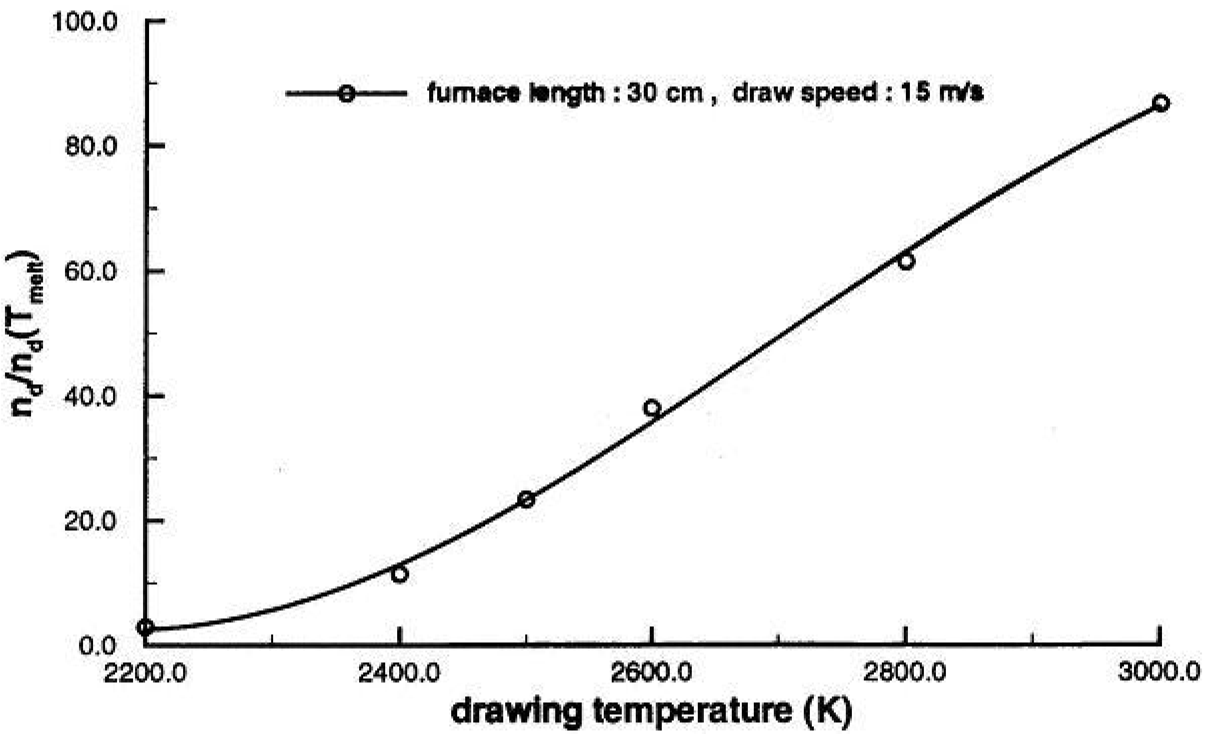


(I) L = 50 cm , V_f = 5 m/s



(II) L = 50 cm , V_f = 15 m/s

Dependence of Average Concentration of E' Defects on Furnace Wall Temperature



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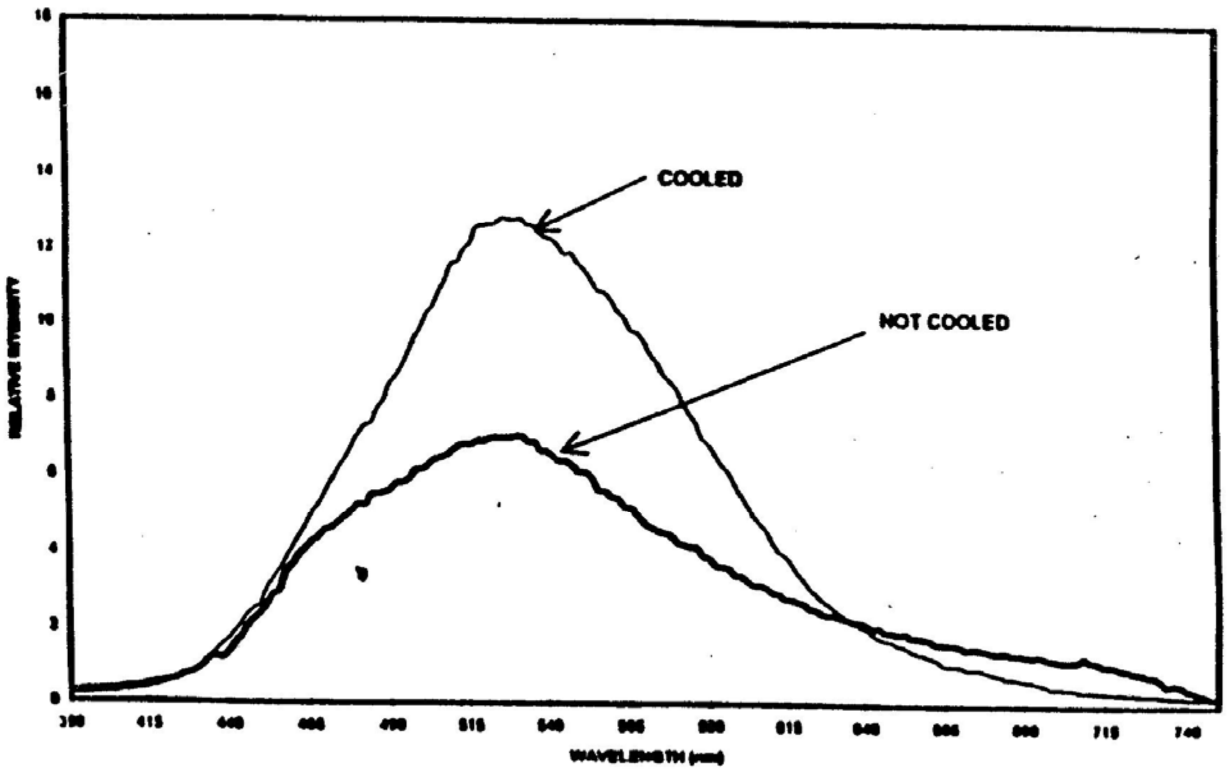
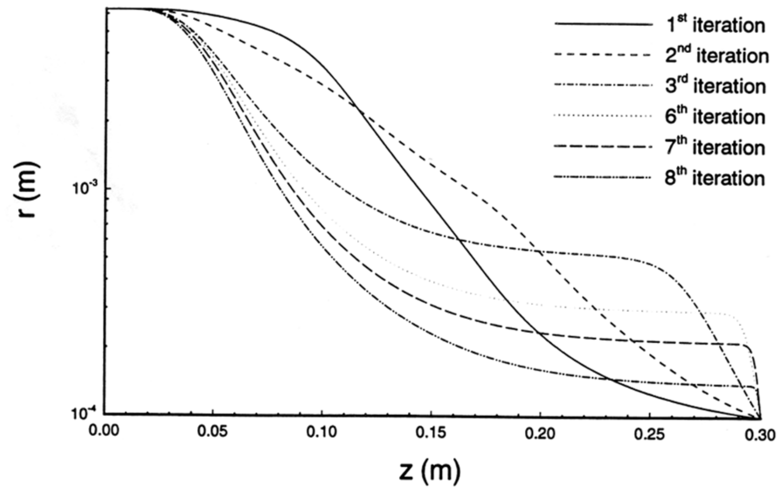
Luminiscence of Fibers Drawn at 2050 C and 80 m/min

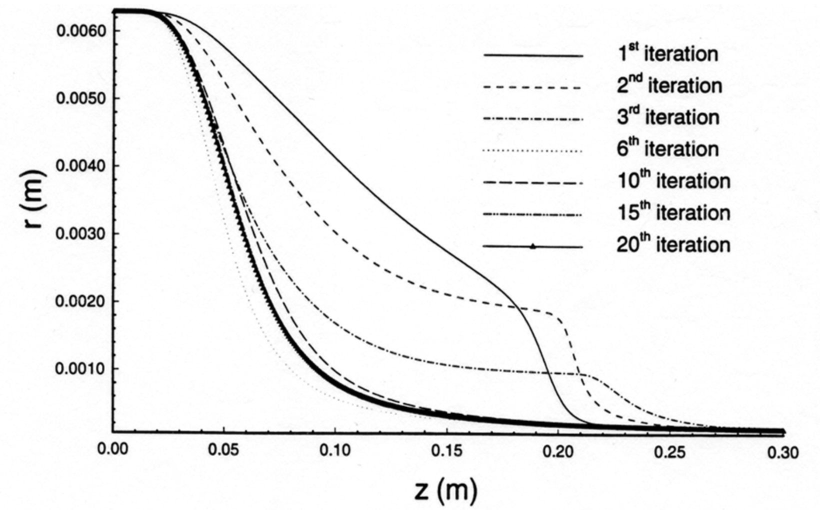


Process Feasibility

Iterative Convergence Of Neck-Down Profile



(a) R_f =100 μm (inability to converge)



(b) R_f =125 μm (iterative convergence)

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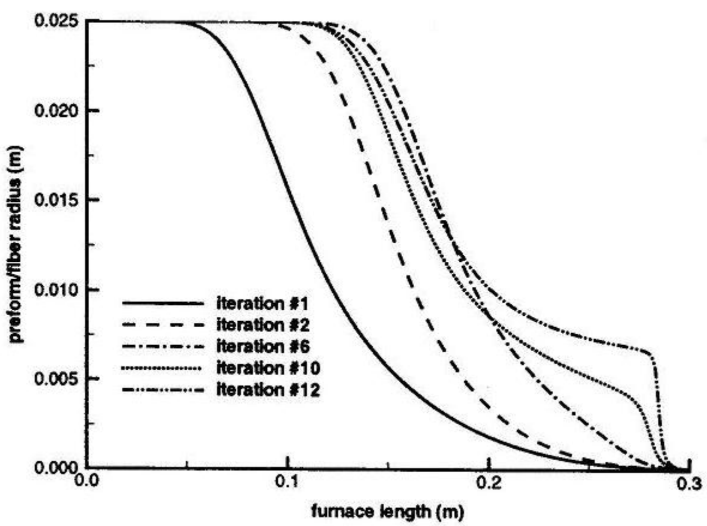
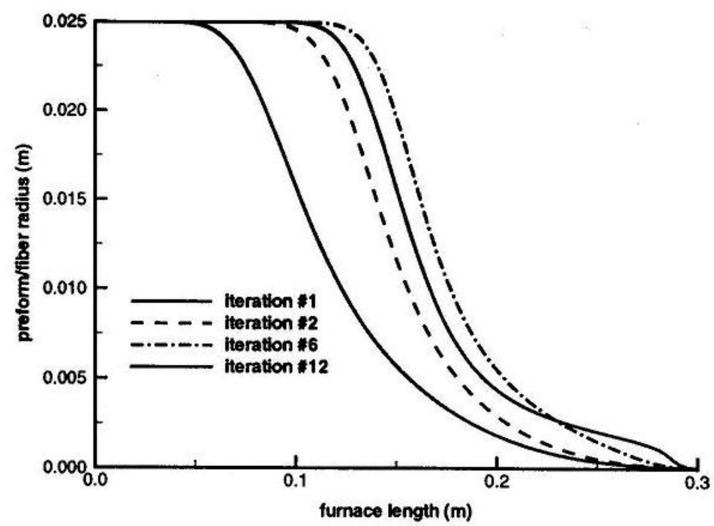
Neck-down Profile Corrections



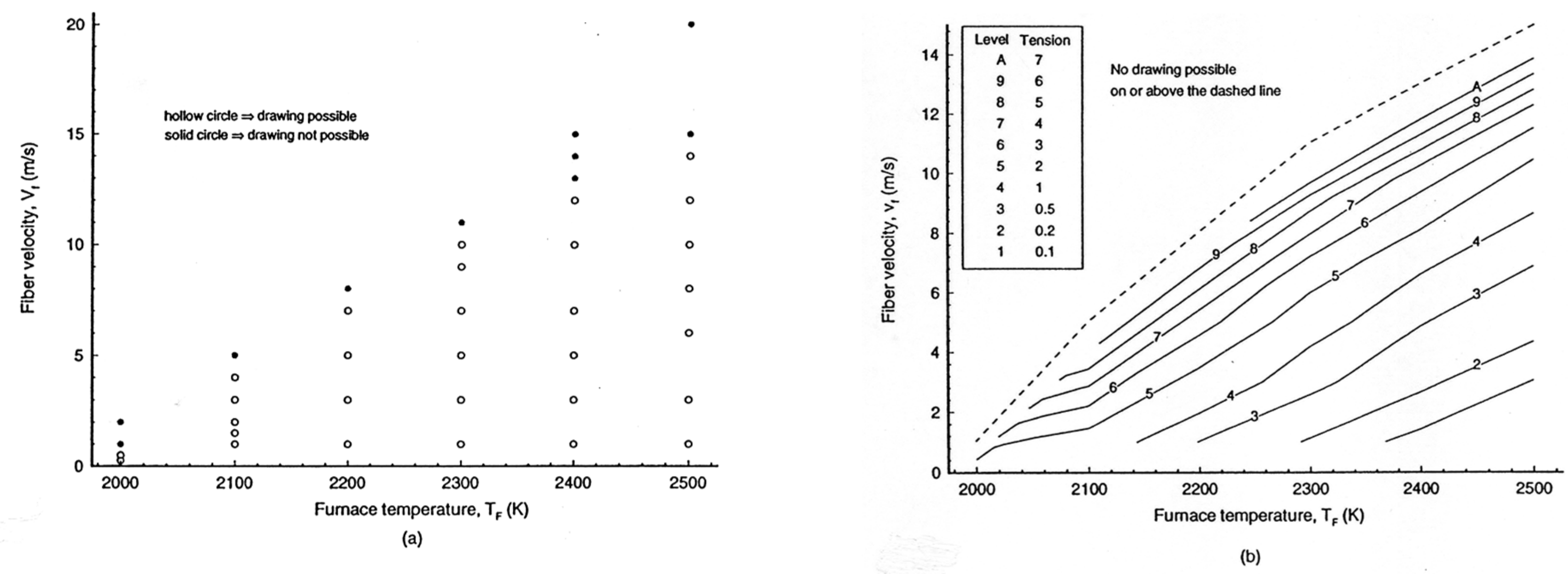
(a)



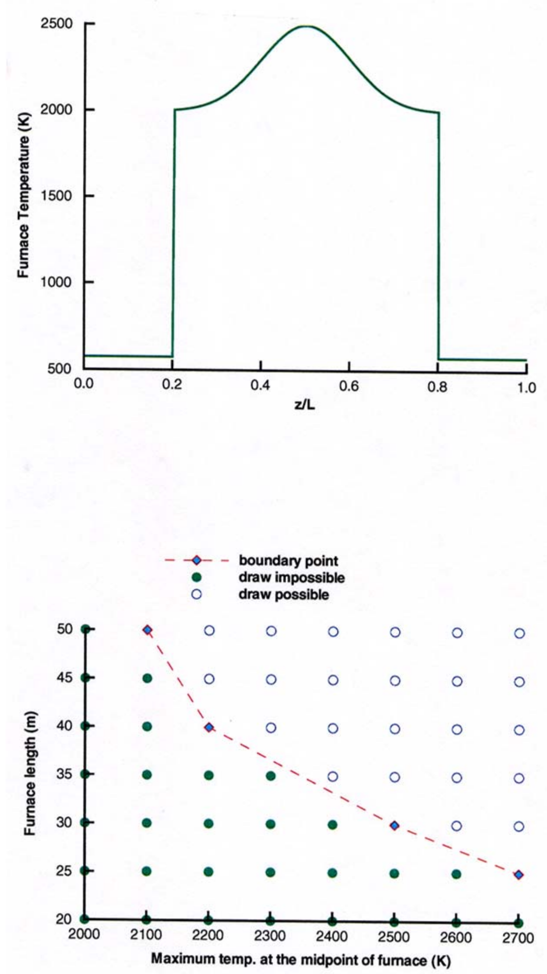
(b)

Neck-down profile corrections for an infeasible fiber drawing circumstance at a furnace temperature of (a) 2300K and (b) 2400K and a draw speed of 15 m/s

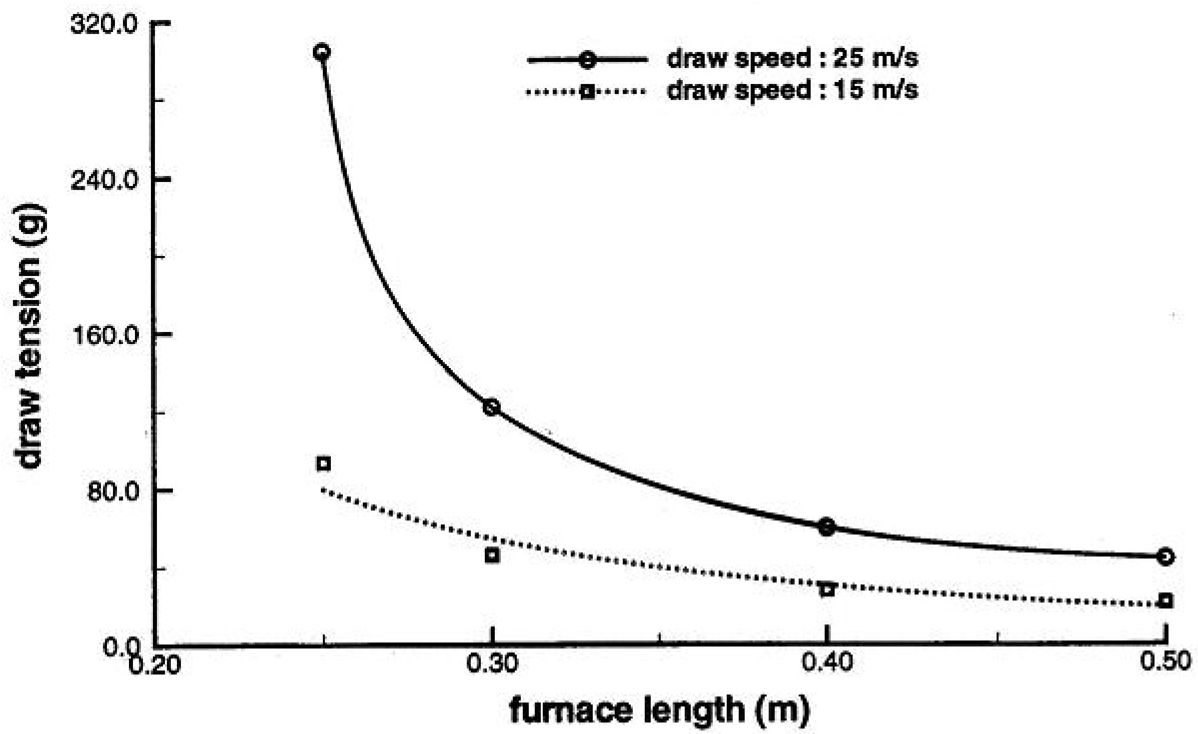
Feasibility Region in Optical Fiber Drawing



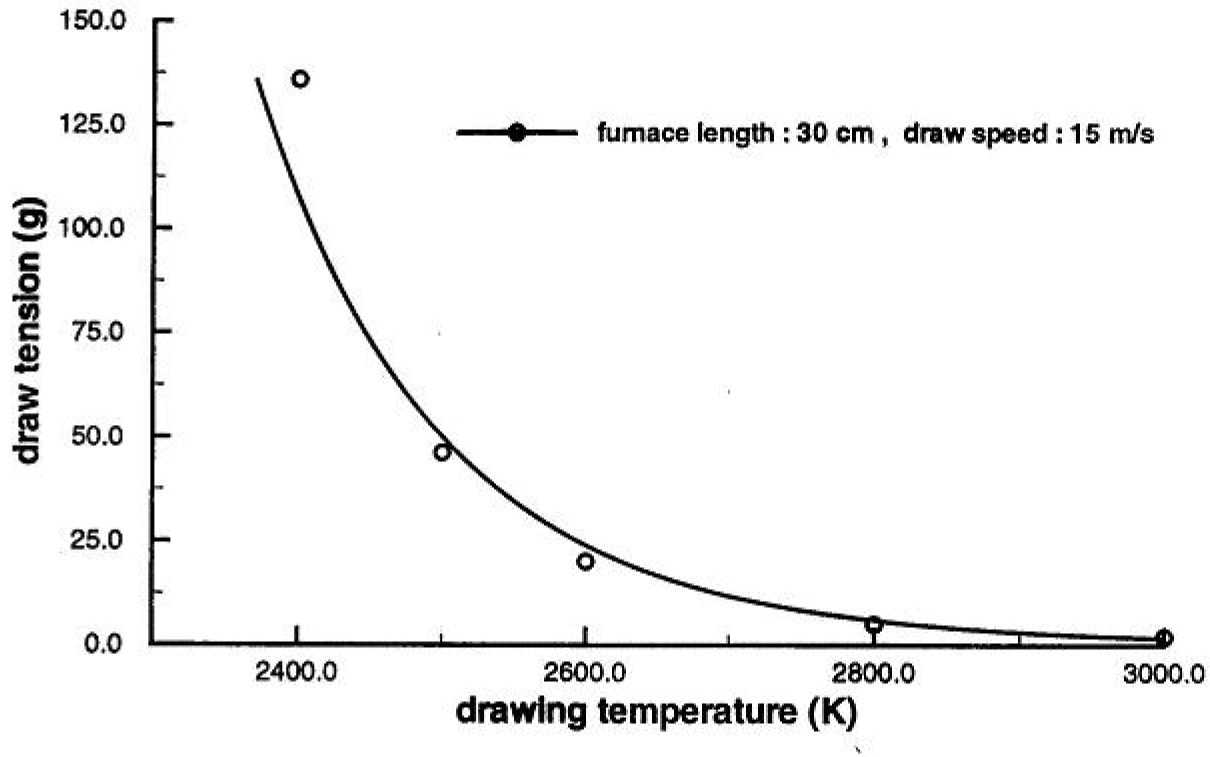
Feasibility Region in Optical Fiber Drawing



Effect of Furnace Length on Tension

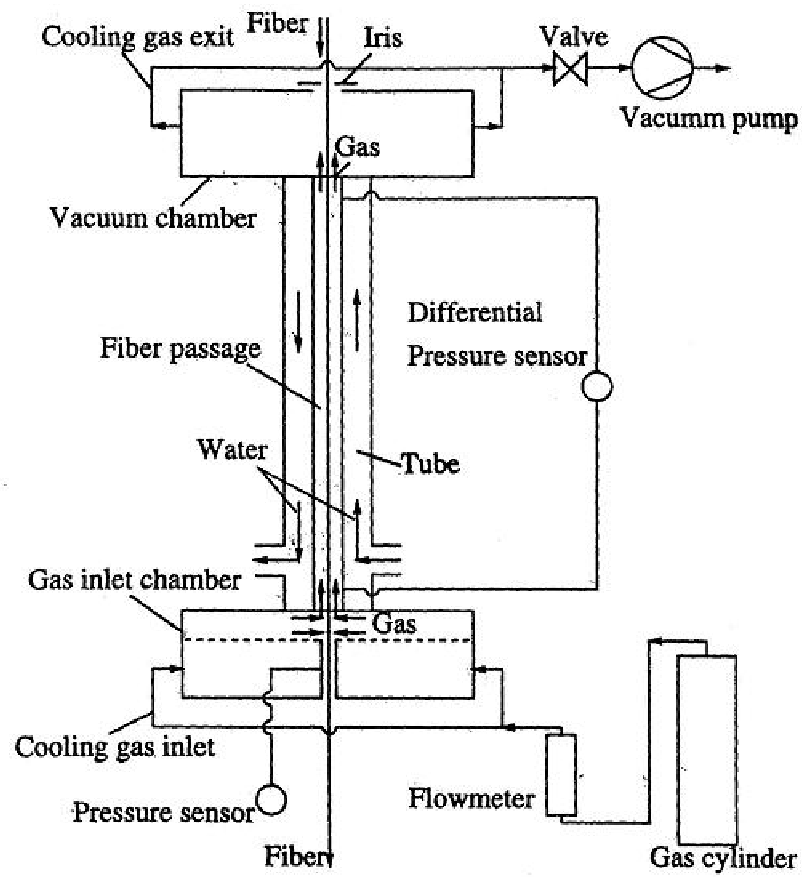


Dependence of Draw Tension on Furnace Wall Temperature

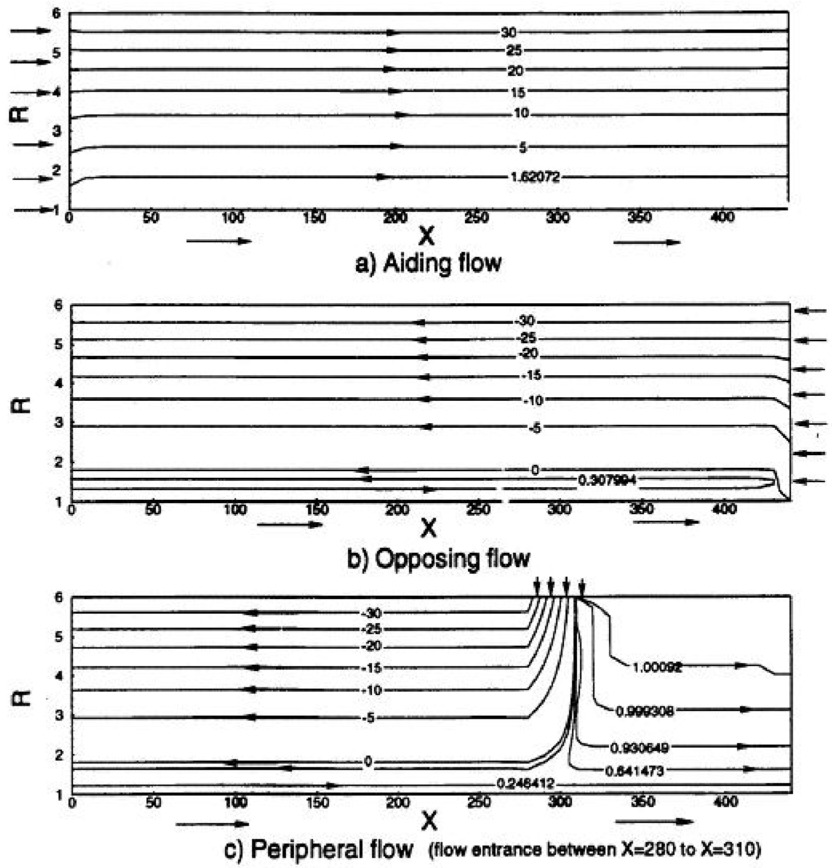


Cooling of Fibers After Draw Furnace

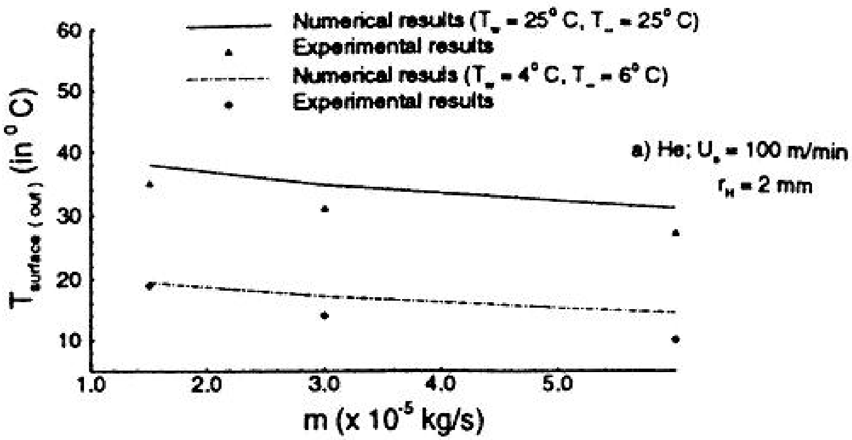
System for Cooling of Fibers

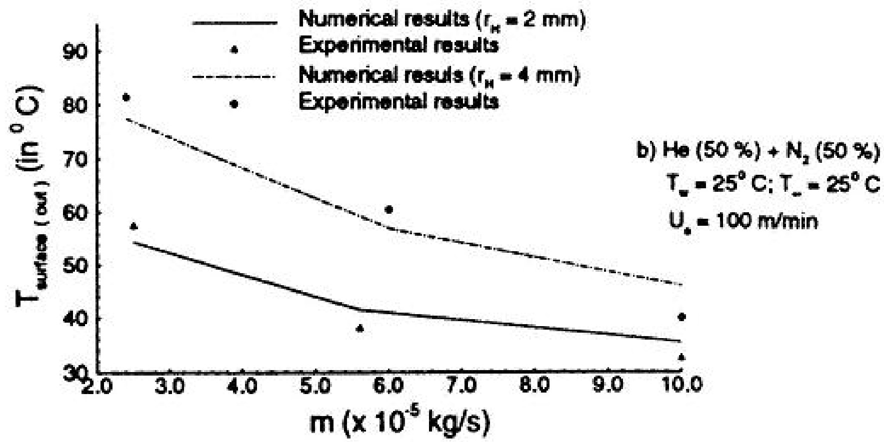


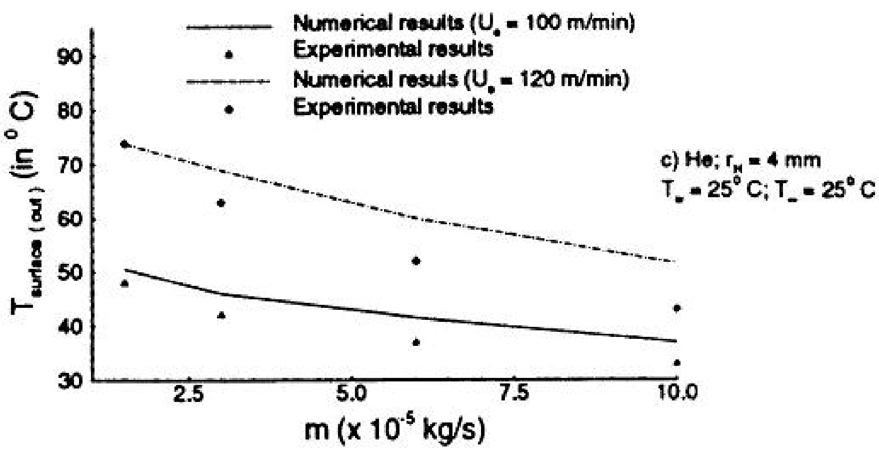
Streamlines for Aiding, Opposing and Peripheral flow



Comparison of the Numerical Results with Experimental Data Obtained by Vaskopulos et al. (1993)







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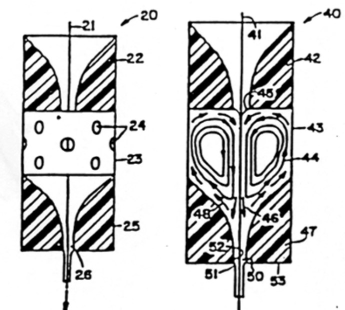
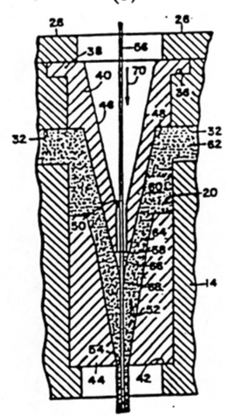
Polymer Coating of Fibers

Typical Coating Applicator Designs

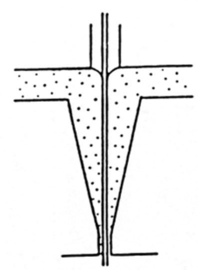


(a)

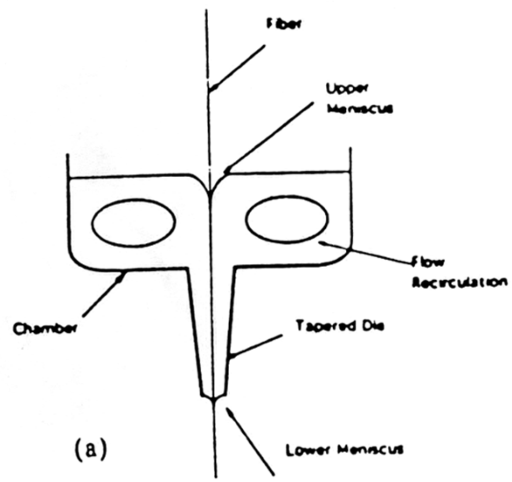
(b)



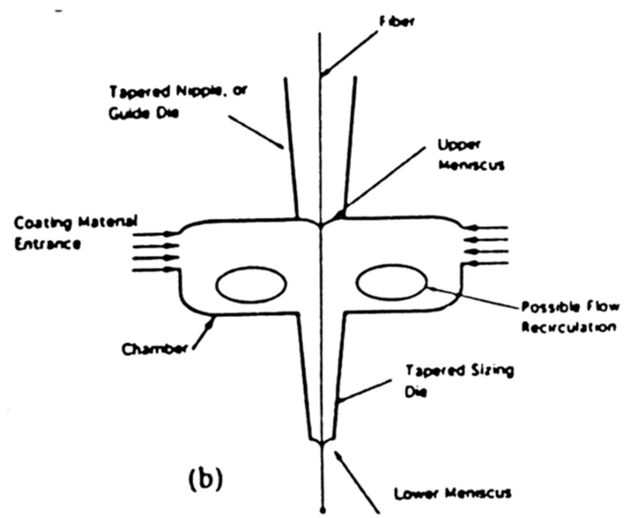
(c)



Flow in Fiber Coating Process



Open-Cup



Pressurized

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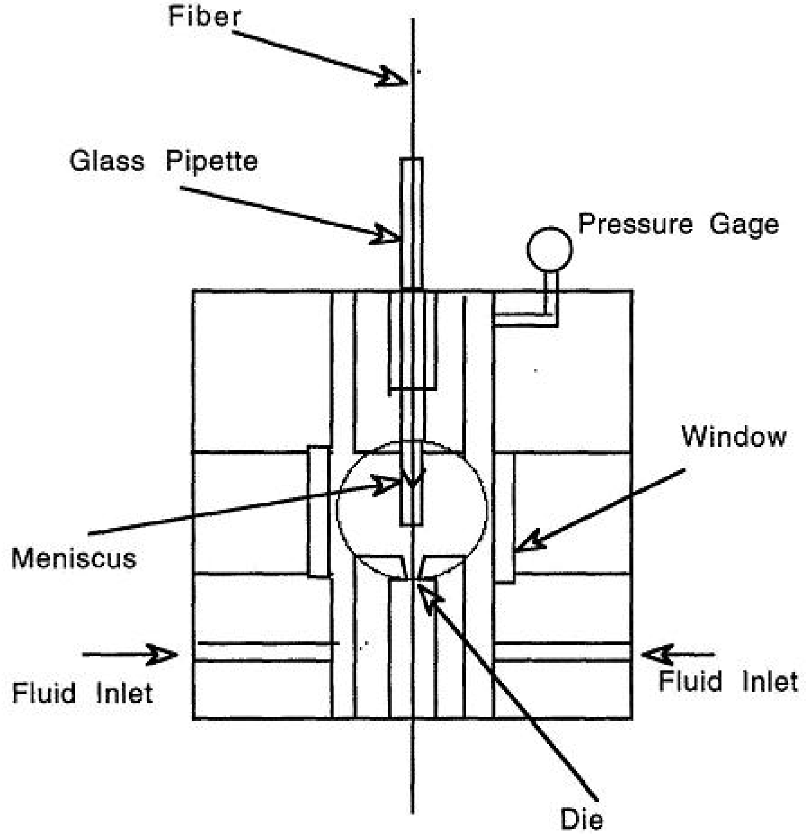
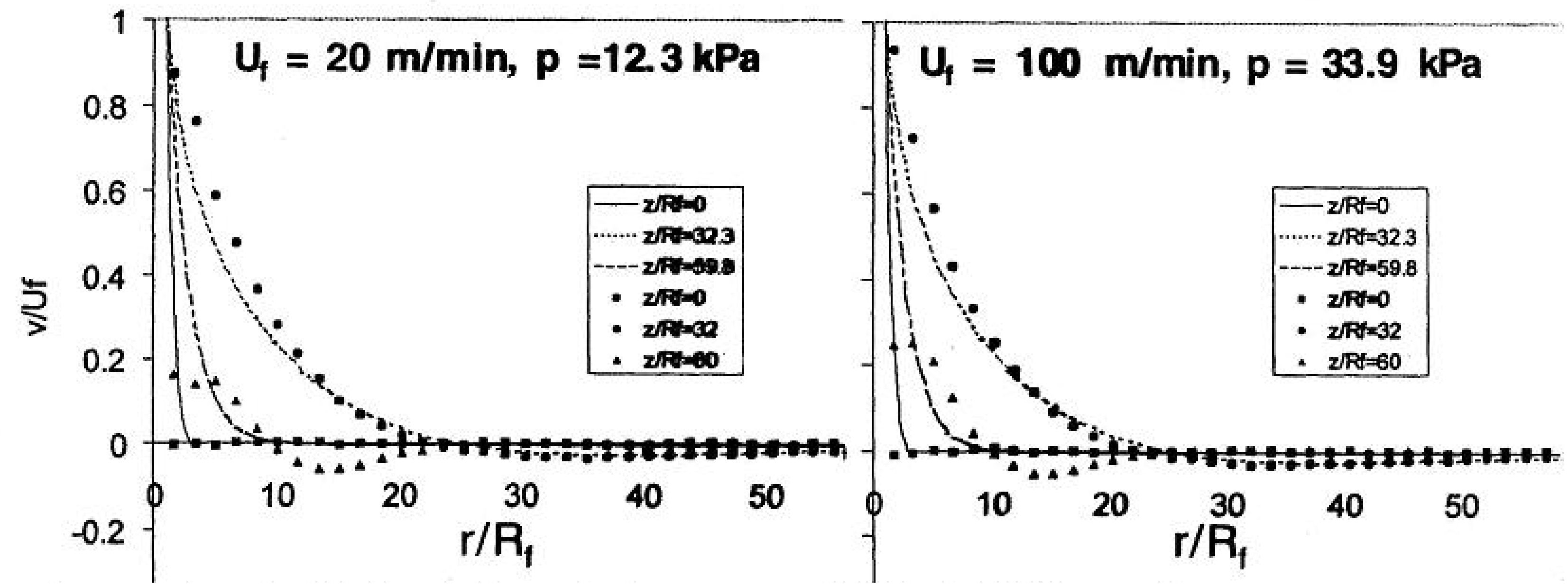
SCHEMATIC DIAGRAM OF A TEST APPLICATION



Measured and Computed Flow Velocities

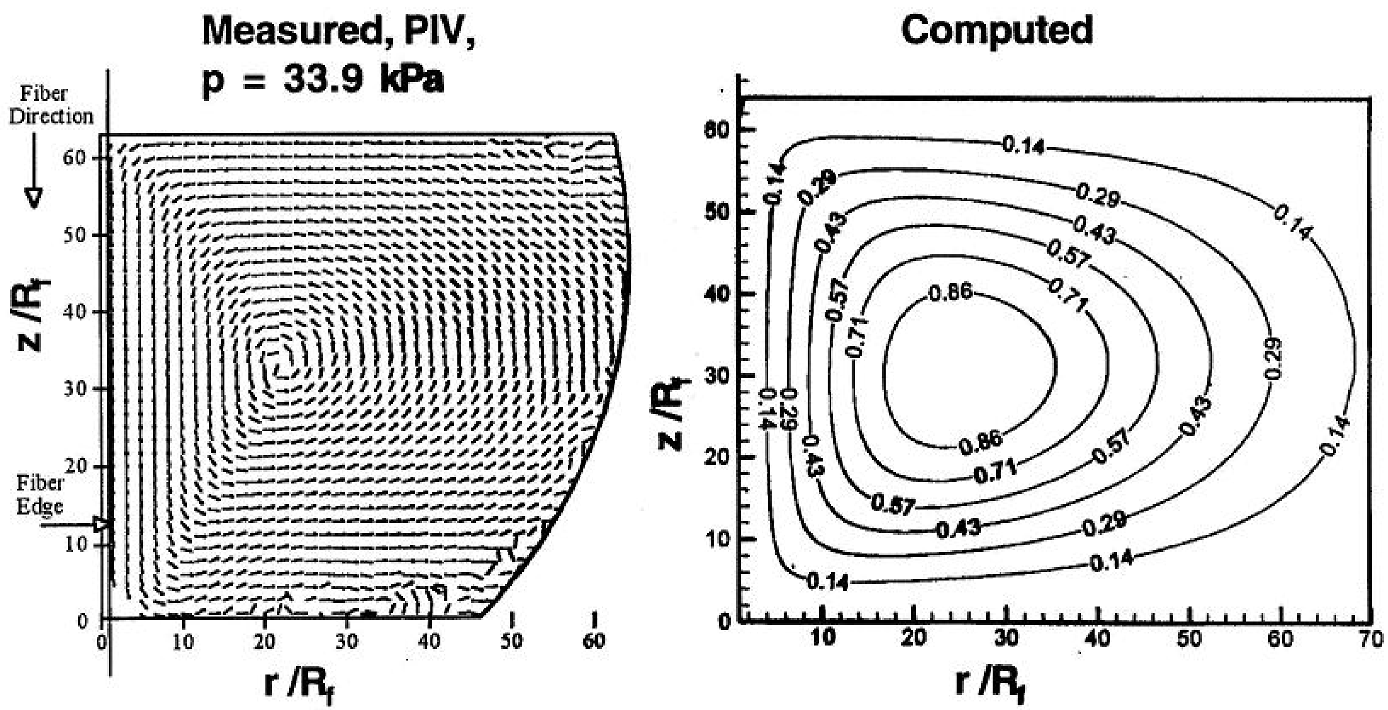


Lines Indicate Computed Results

r / R_f = **Radial distance from the fiber**

z / R_f = **Axial distance from the exit die**

Particle Pathlines and Computed Flow Streamlines



Fiber Speed: 100 m/min

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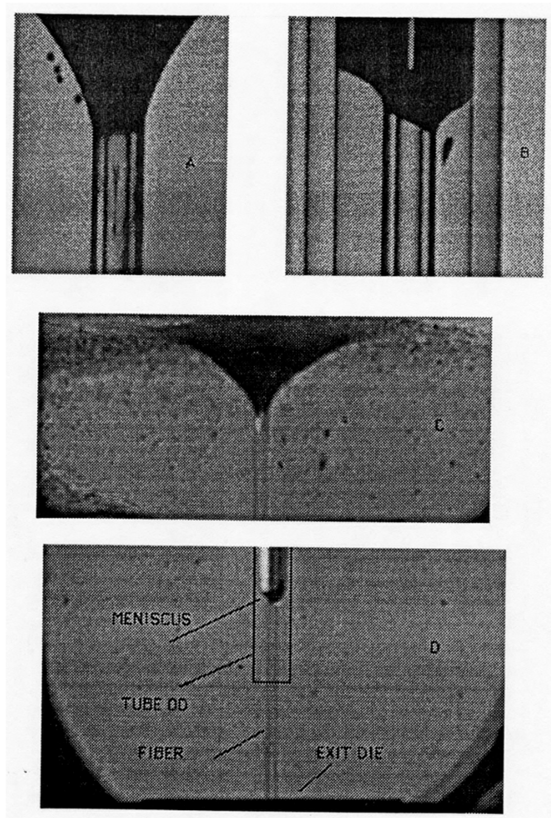
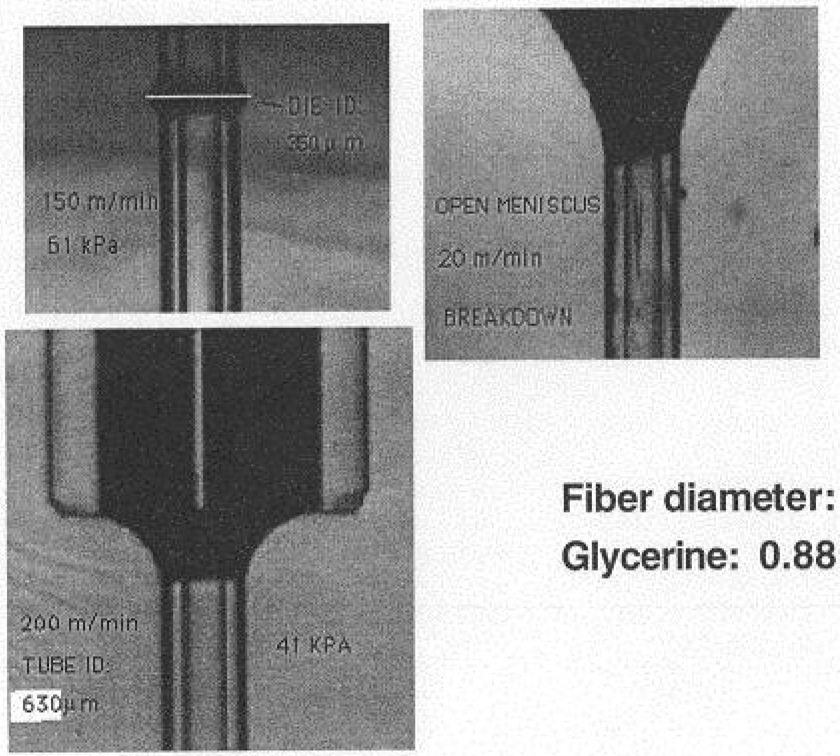
Meniscus in Fiber Coating Process



A, C: Unpressurized

B, D: Pressurized

Meniscus Size Depends on Fiber Speed, Pressure and Inlet Diameter

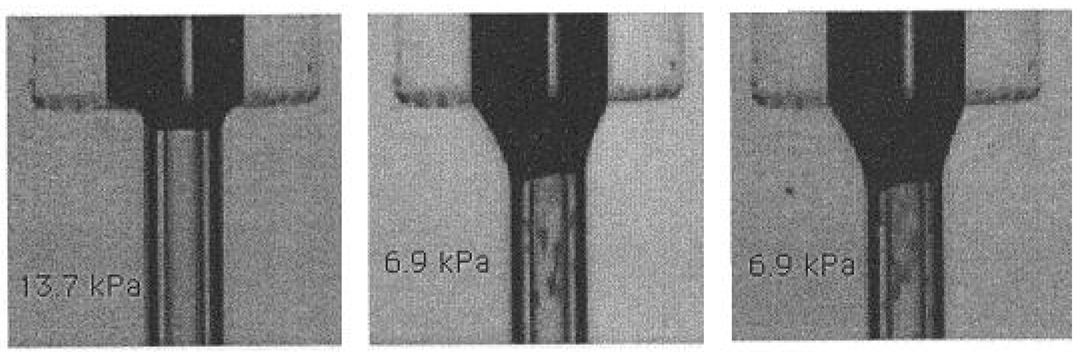


Fiber diameter: 254 μm

Glycerine: 0.88 N sec/m²

Sufficient Decrease in Pressure Results in Meniscus Breakdown

Fiber diameter : 254 μm
Tube ID : 460 μm
Glycerine: 0.88 N sec/m²
Fiber speed: 40 m/min



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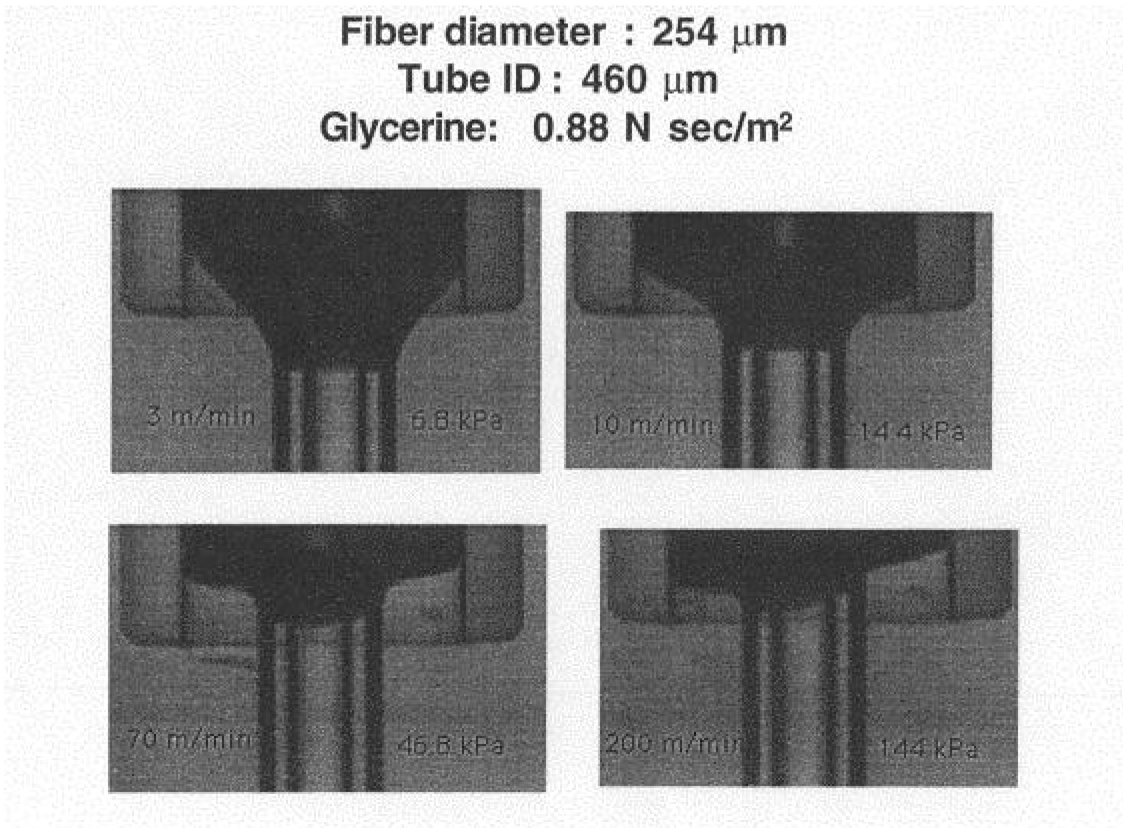
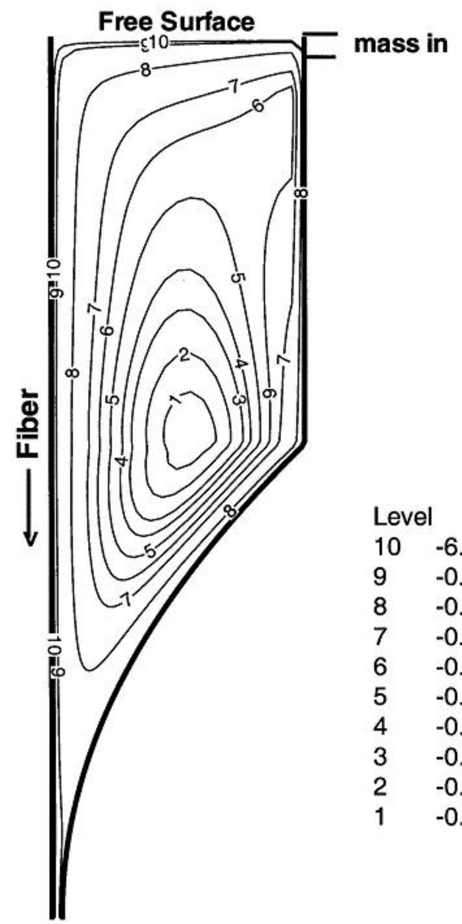
Increase in Applicator Pressure Flattens The Meniscus



Stream Function Distribution for Fiber Speed of 10 m/s



Level	$\Psi(10^{-3})$
10	-6.07102E-05
9	-0.000144111
8	-0.000696718
7	-0.00155396
6	-0.0021602
5	-0.00280297
4	-0.00346678
3	-0.00398131
2	-0.00470679
1	-0.00539917

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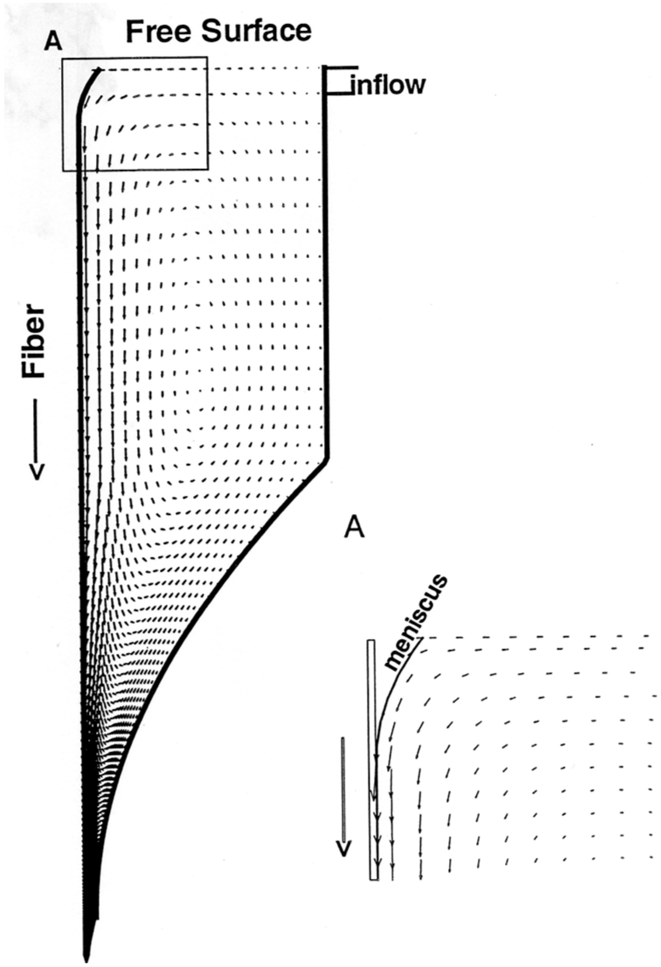
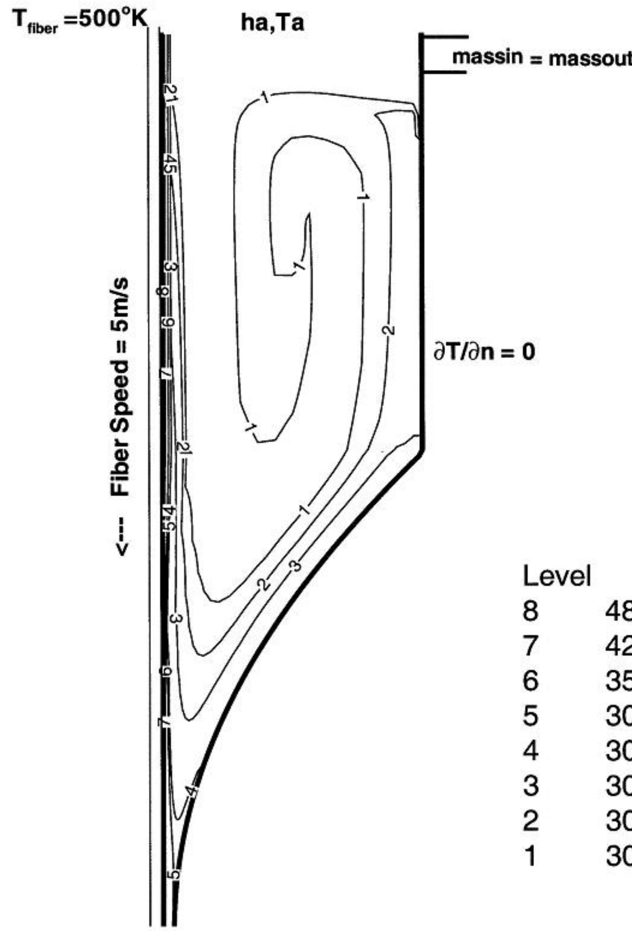
Effect of Meniscus



Temperature Contours for Fiber Speed of 5m/s, with Adiabatic Wall Boundary Condition



Level	T°K
8	481.274
7	427.16
6	358.102
5	304.918
4	303.751
3	301.314
2	300.595
1	300.294

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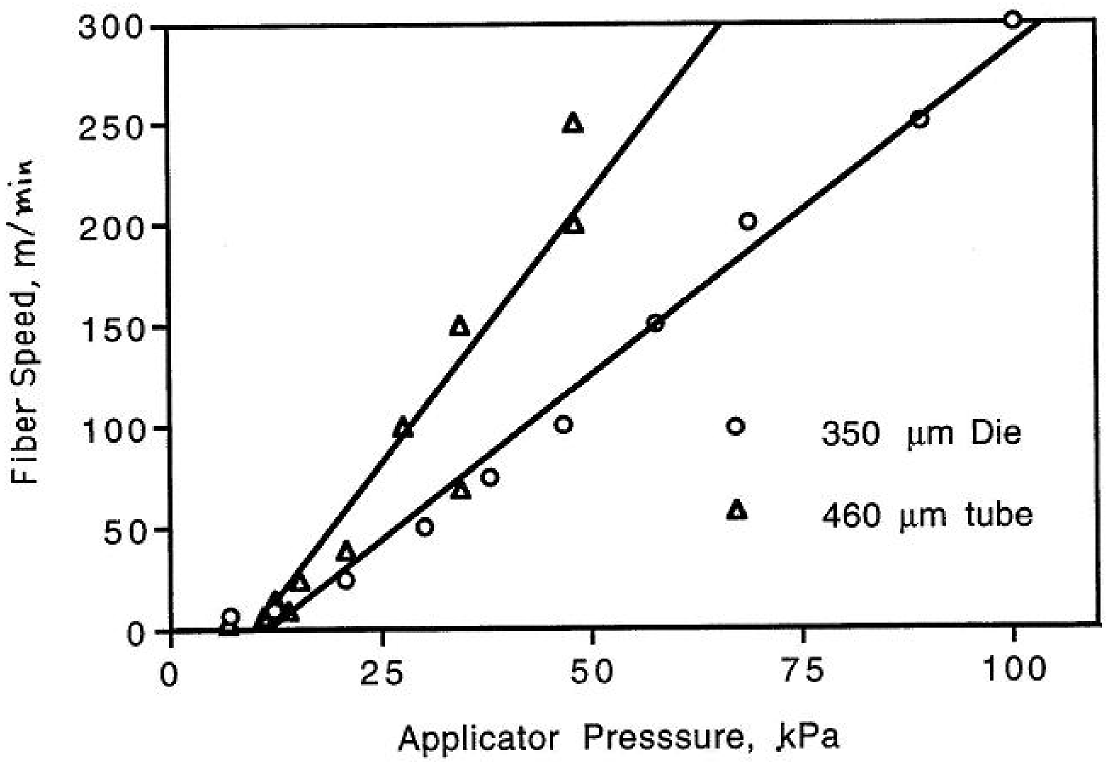
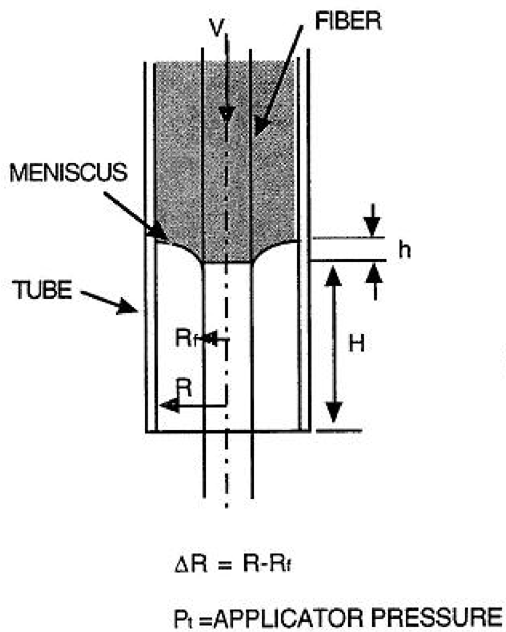
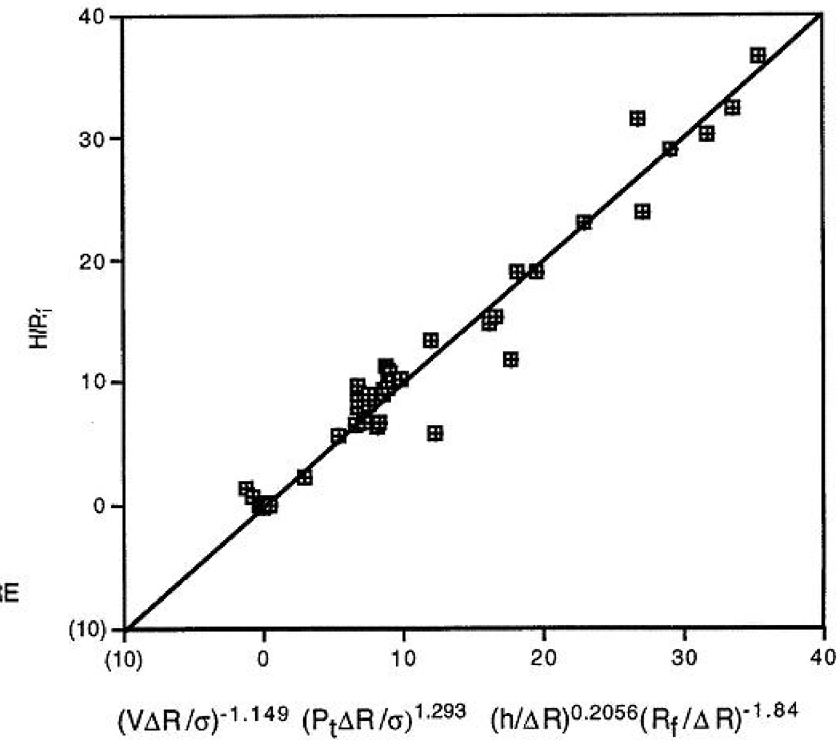
Applicator Pressure vs. Fiber Speed for Maintaining Entrance Meniscus Near Tube or Die Exit



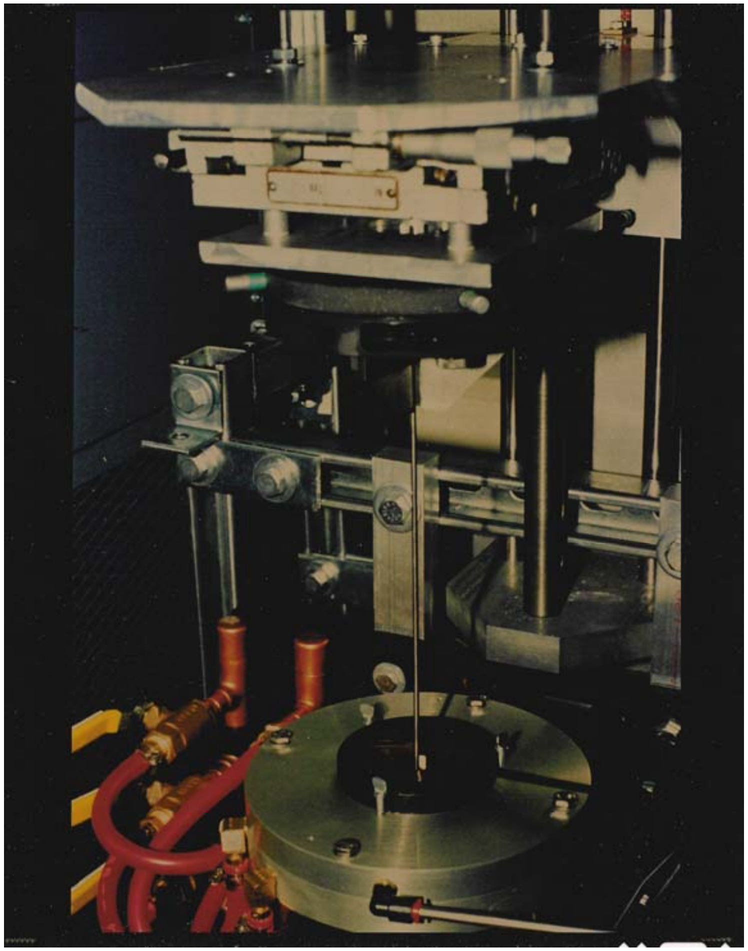
Correlation of Meniscus Position within Entrance Tube



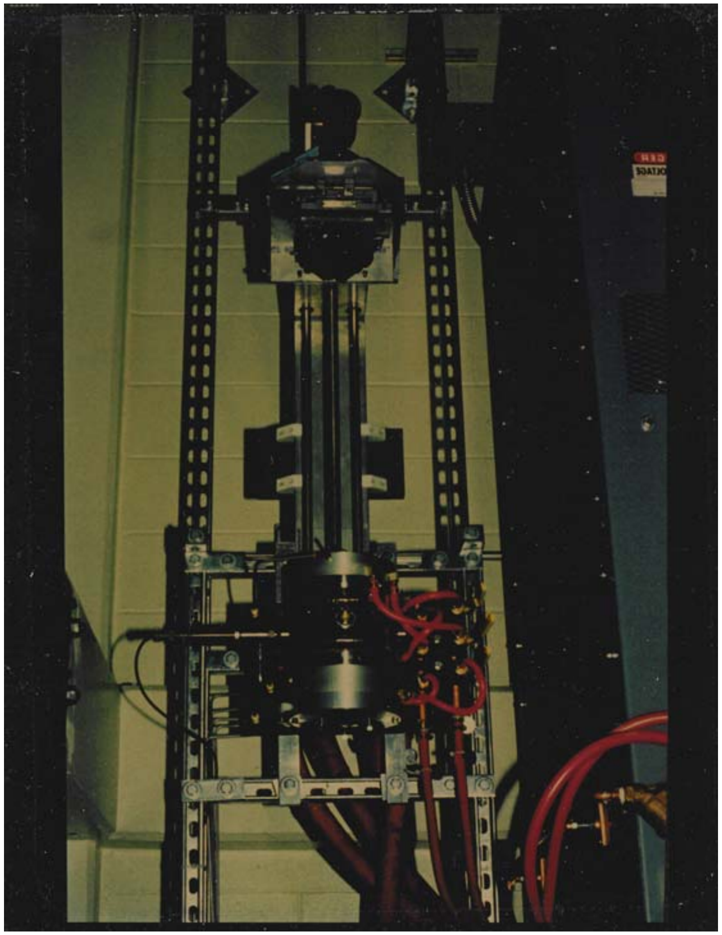


Inverse Problem for Furnace Wall Temperature Measurement

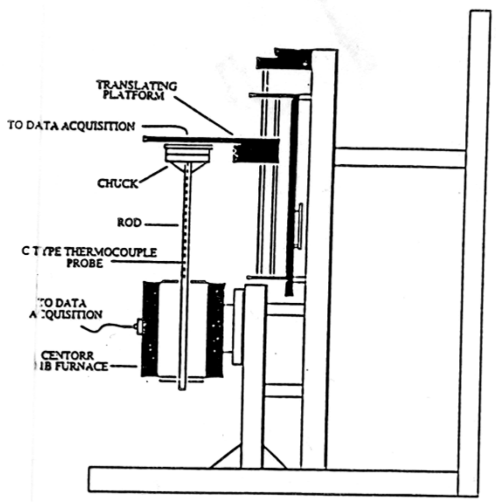
Temperature Measurements in the Furnace

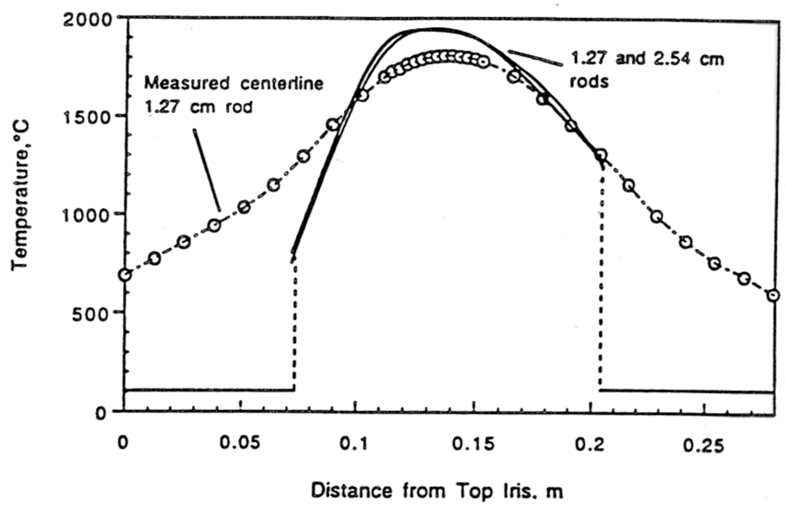


Temperature Measurements in the Furnace



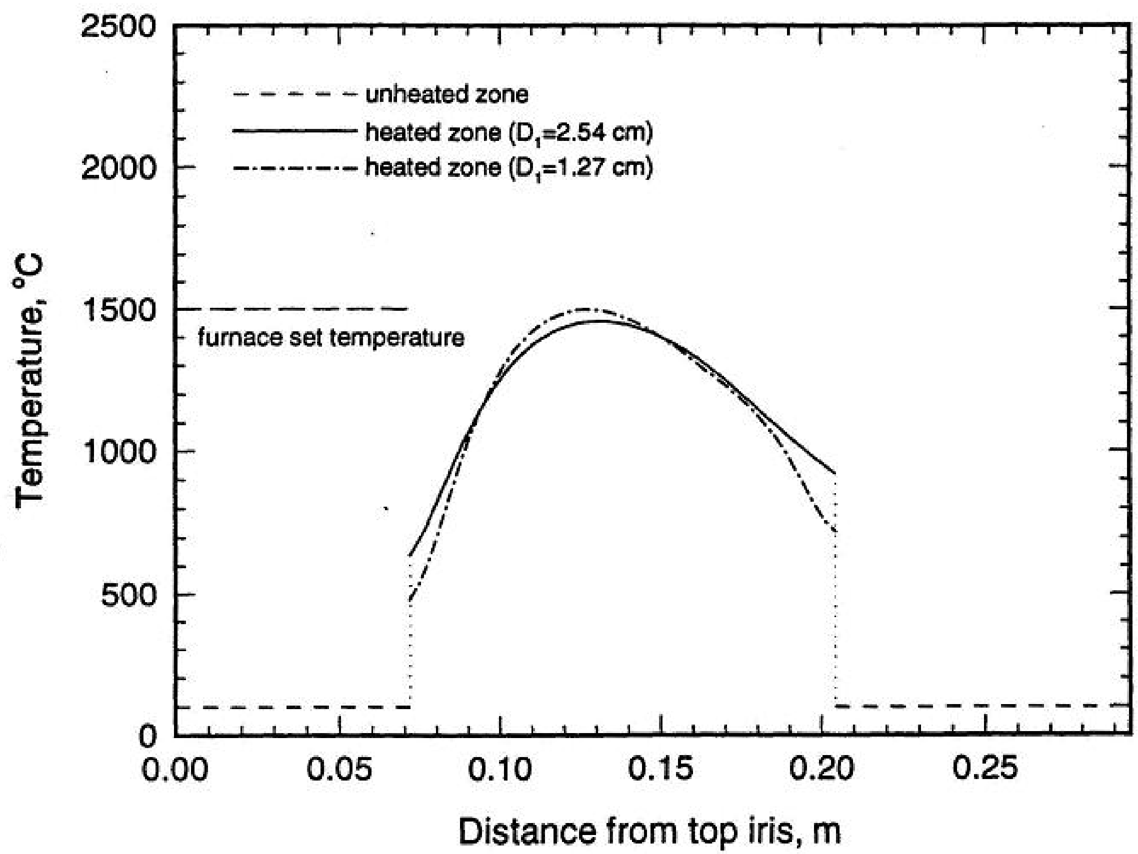
Inverse Calculation to Obtain Furnace Temperature Distribution





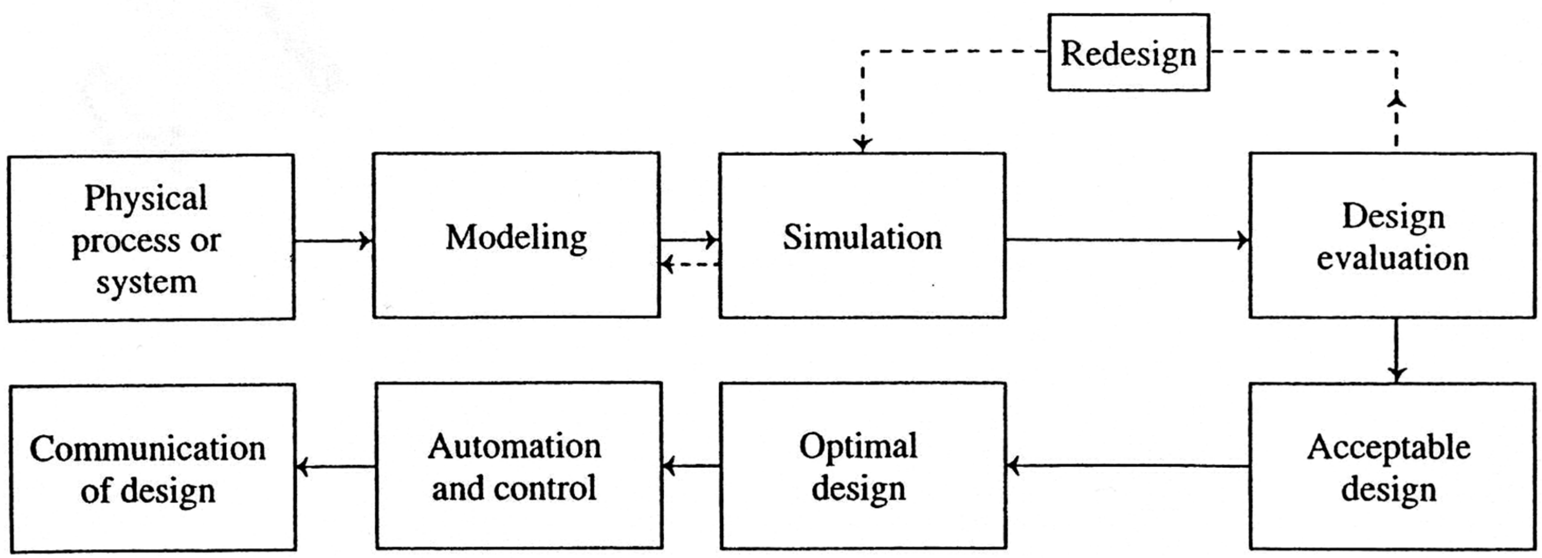
Computed Furnace Axial Temperature Distributions for Different Graphite Rod Sizes

$$T_f = 1500^\circ C$$

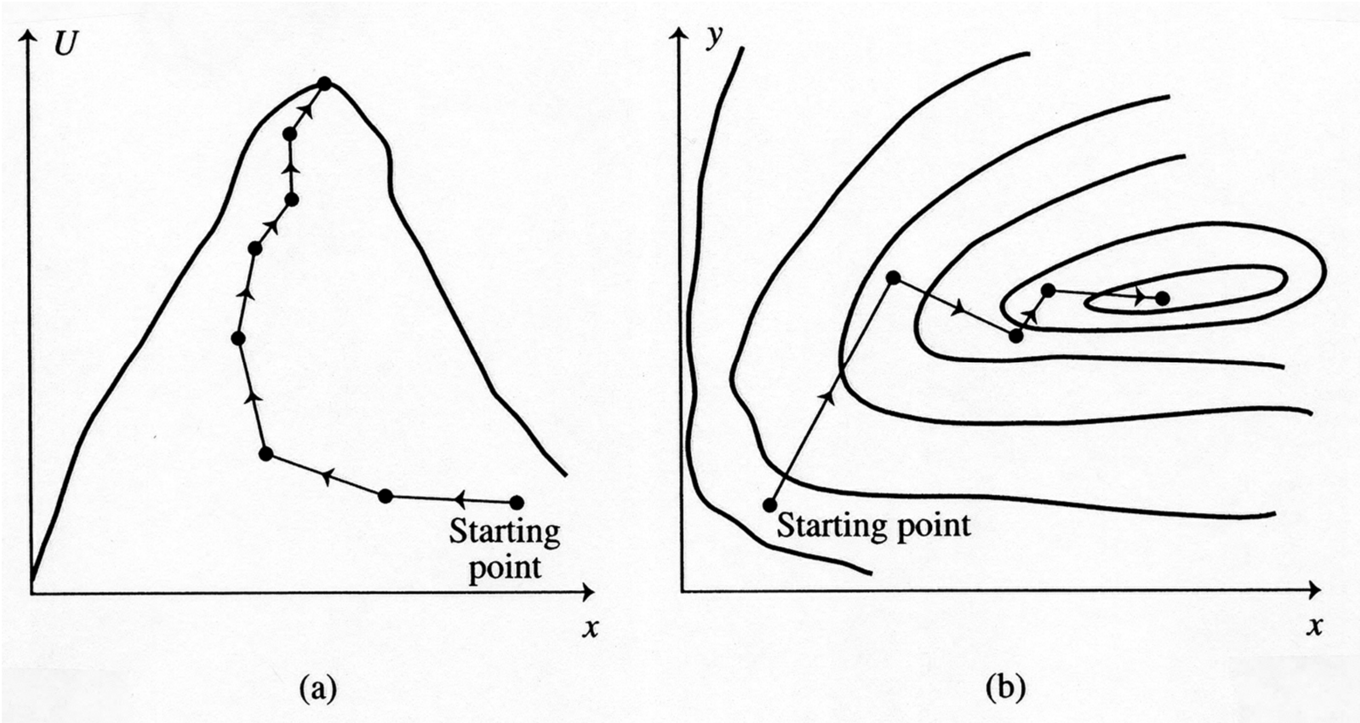


Design and Optimization

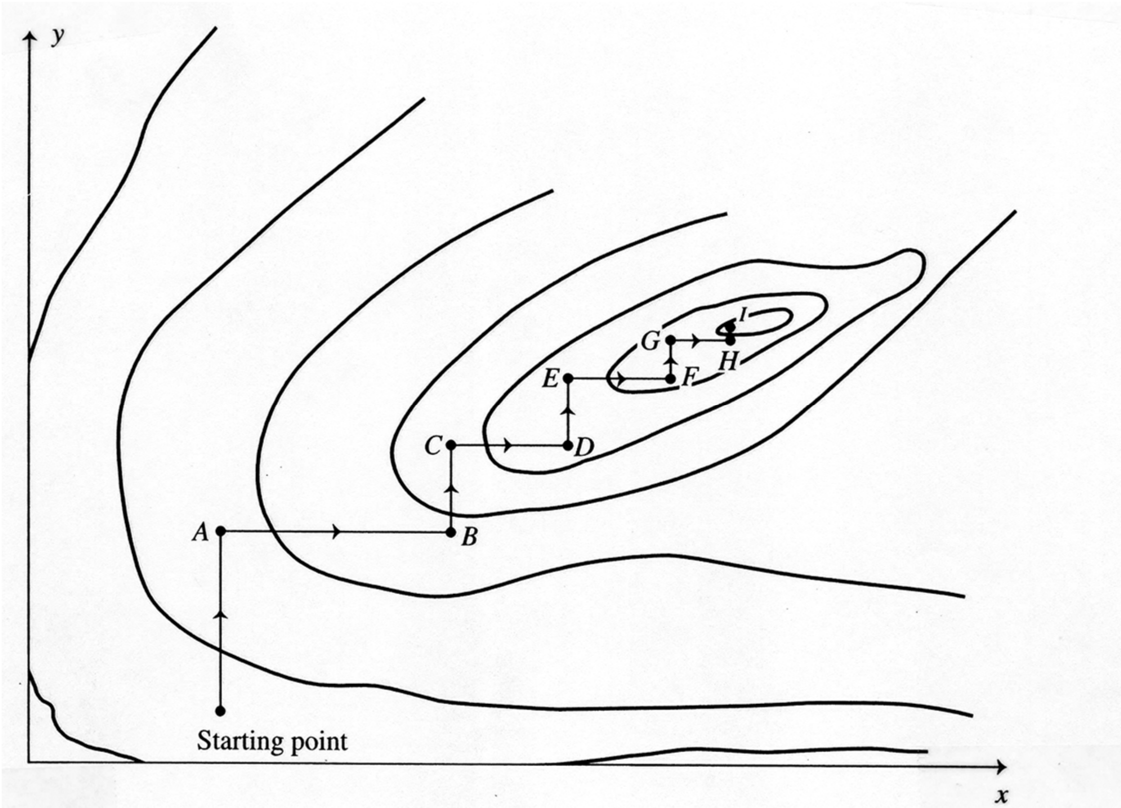
Typical Steps in Design and Optimization



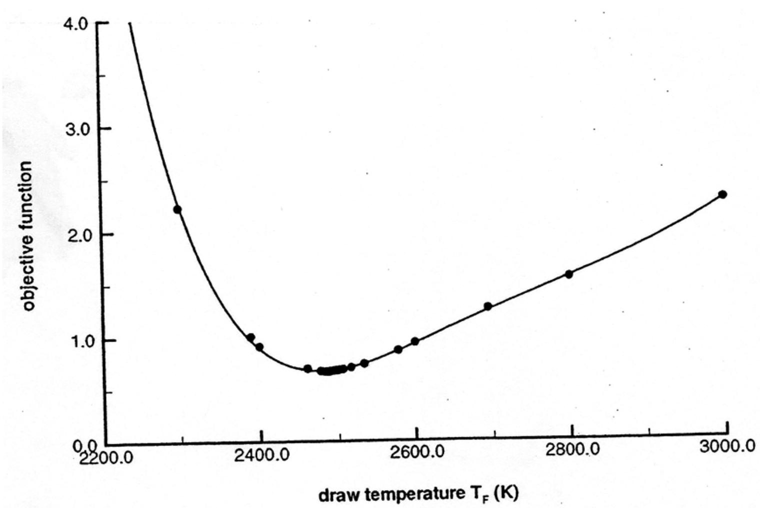
Steepest Ascent Method for Optimization

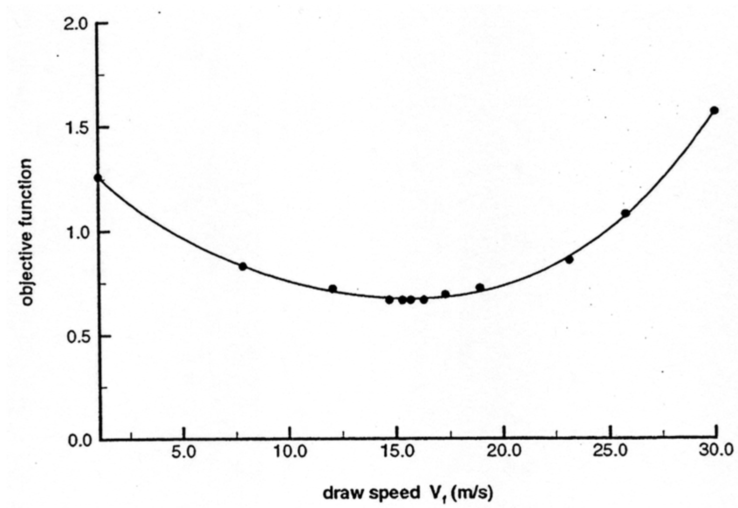


Univariate Search for Optimization



Optimization of an Optical Fiber Drawing System





U = (Operating Cost x Defect Conc.) / Production Rate

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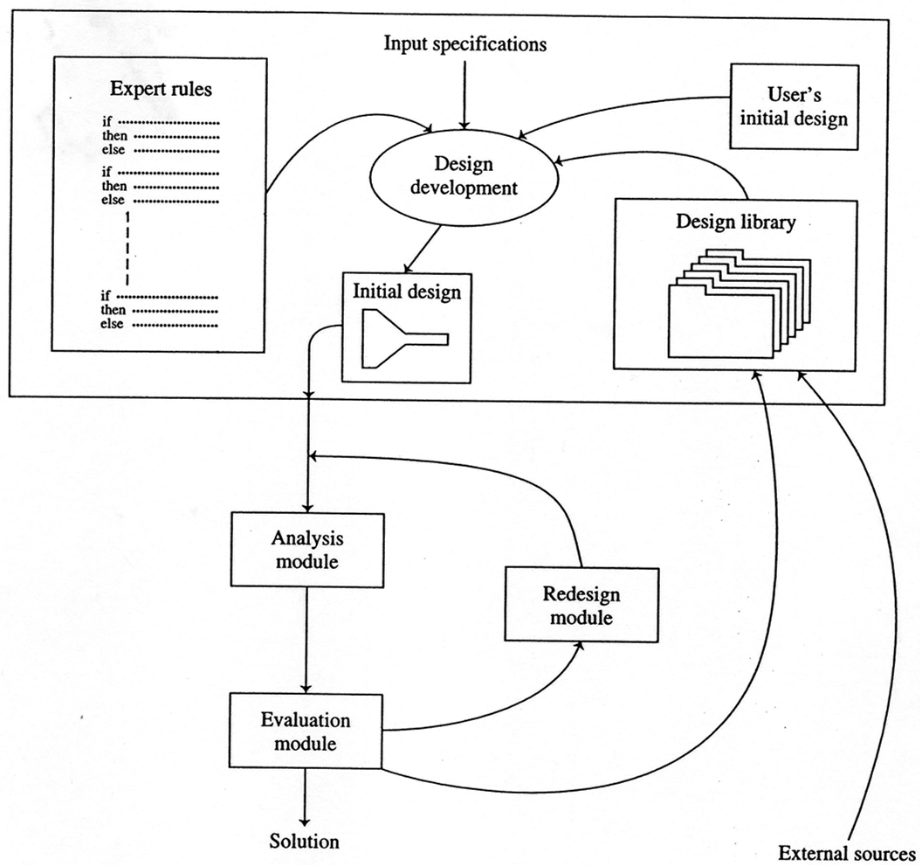
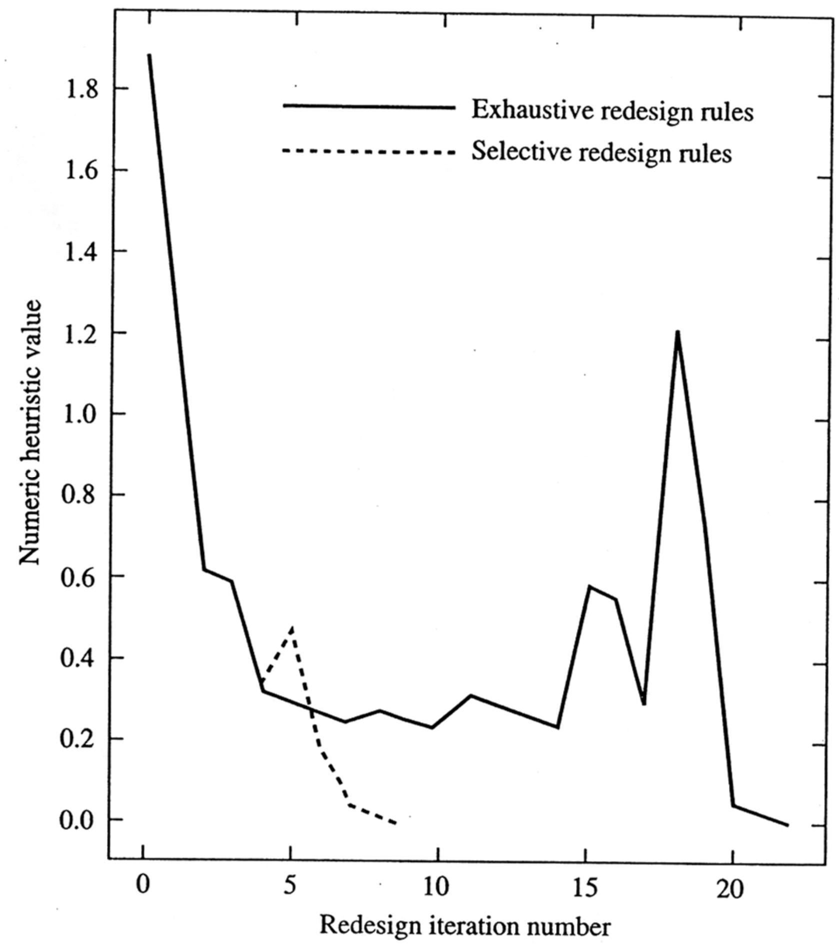
Development of an Initial Design



Convergence using Knowledge Base



Future Research Needs

- Need Better Link Between Research and Practice
- Validation, System Simulation, Feasibility, Control, Design and Optimization
- Strong Need for Material Properties
- Experimentation for Validation and Insight
- Coupling of Micro- and Nano- Scale with Macro-scale
- Effect on Material and Product Characteristics

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