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THE DYNAMICS OF THIN-FILM BREAKUP IN A CONSTRICTED PORE

P.A. Gauglitz and C.J. Radke

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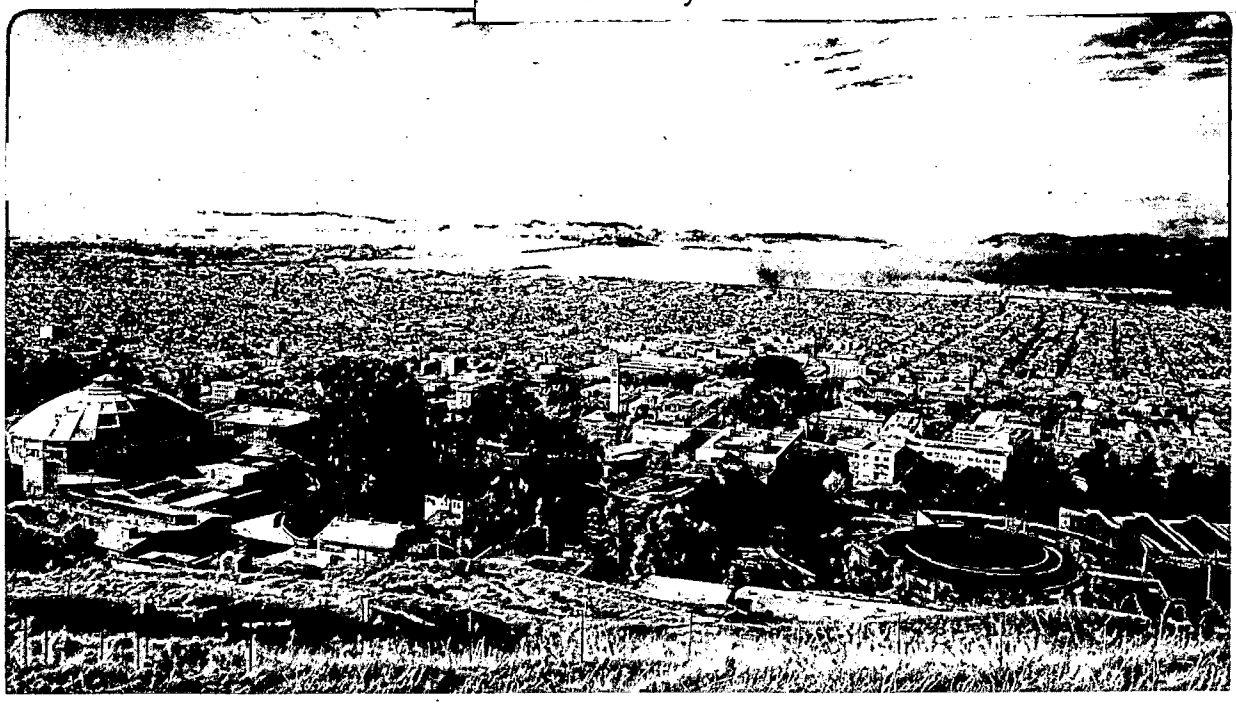

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The Dynamics of Thin-Film Breakup in a Constricted Pore

by

P.A. Gauglitz and C.J. Radke

Chemical Engineering Department

University of California

Berkeley, CA 94720

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P.A. Gauglitz (Speaker) and C.J. Radke
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ABSTRACT

To understand foam formation in porous media, this work considers the dynamics of a wetting liquid film forming an unstable collar (or collars) in a constricted cylindrical tube. A hydrodynamic lubrication analysis is presented to describe the time evolution of a thin viscous film under the influence of surface tension and conjoining or disjoining forces. Time to breakup depends on the pore shape, the strength of the conjoining or disjoining force, the initial film profile, and also, the fluid viscosity, interfacial tension, and unconstricted pore radius which combine to form a characteristic scaling time.

Agreement is found between breakup times predicted from the hydrodynamic analysis, and from 16 mm movies taken of the breakup phenomena over a wide range of initial film thicknesses.

Introduction

The success of enhanced oil recovery depends on how efficiently an injected fluid can displace the oil residing in a reservoir. With good mobility control, the injected fluid moves as a plug and optimal displacement efficiency results. In a gas (or steam) drive, the mobility ratio is unfavorable, and poor displacement efficiency occurs because the gas (or steam) bypasses the oil due to gravity override and fingering.

Displacing with foam rather than gas is a promising technique for improving mobility control in a gas or steam drive (Bernard and Holm, 1964). In porous media, a "foam" consists of gas bubbles, either larger or smaller than the pore size, separated by liquid lamellae which are stabilized by surfactants.

Typically, a mixture of gas and surfactant solution is injected into the porous medium, and evolves into a foam as it flows. However, the mechanisms which generate the foam in-situ are not well understood. This work investigates the bubble generation mechanism and presents a first step towards predicting the in-situ bubble size. Such understanding is important because the flow properties of the foam depend strongly on the size of the generated bubbles (Hirisaki and Lawson, 1983).

Bubble generation by snap off at pore necks is an important mechanism for foam generation (Mast, 1972). Snap off occurs as a gas bubble moves through a constriction and leaves behind a film of wetting liquid (Brethreton, 1961; Park and Homsy, 1984; Taylor, 1961). This film is unstable to flow of liquid into a collar at the pore neck. Eventually, enough liquid collects in the collar to block the pore, and a new bubble is formed. In this work, we model the key step in snap off: the dynamics of a thin, curved viscous film of

wetting liquid forming an unstable collar at a pore neck and snapping off to generate a bubble.

A general form of the evolution equations for interfacial waves has been derived (Atherton and Homsy, 1976), and the evolution of a thin film in a straight cylindrical tube has been previously investigated (Hammond, 1983). In this work, we consider a constricted cylindrical tube, and we include the influence of thin-film forces (i.e., conjoining and disjoining forces) which become important in extremely thin films.

Theory

Consider a viscous film of liquid wetting the inside wall of a constricted pore as shown in Fig. 1. Cylindrical coordinates are used with the axial origin at the neck of the constriction. The radius of the unconstricted pore is R_T, and the dimensionless position of the film interface is given by $\kappa(\tilde{x})$. The shape of the constriction is given by the arbitrary function $\lambda(\tilde{x})$. For the results reported here, we define the pore shape with a cosine function as follows:

$$\lambda(\tilde{x}) = 1 - 0.4\ [1 + \cos(\tilde{x}\pi/10)]\ . \qquad (1)$$

Since the film interface is not of constant curvature, surface tension drives the fluid in the film towards the neck. To determine the flow rate of liquid in the film, we employ the classical lubrication approximation by restricting our analysis to situations where the slope of both the pore wall and the film interface are small. In addition, if the film is thin, inertial effects are negligible, and rectangular coordinates can be used. The result is a flow equation where the flow rate is proportional to the pressure driving force and to the cube of the local film thickness.

The pressure driving force is obtained from a normal stress balance at the film interface. With the approximations previously mentioned, the pressure is determined by the surface tension and the linearized mean curvature of the interface. We also correct the surface tension by the disjoining pressure which becomes important in films less than about 1 μm in thickness. The functional form for the conjoining and disjoining pressure by Teletzke (1983) is used in our analysis:

$$\Pi(H) = \begin{cases} -A/H^3 & \text{conjoining (attractive)} \\ A/H^3 & \text{disjoining (repulsive)} \end{cases} , \qquad (2)$$

where A is dimensional scaling coefficient. A is related to the Hamaker constant and typically has values near 10^{-21} J (Kruyt, 1952).

An evolution equation for the position fo the film interface is obtained by combining the normal stress balance and the flow equation with an integral form of the kinematic condition to yield:

$$\begin{aligned} \frac{\partial \kappa}{\partial \tau} = & \frac{-\lambda(\lambda-\kappa)^3}{\kappa} \kappa_{xxxx} - \left[\frac{(4\lambda-\kappa)(\lambda-\kappa)^2}{\kappa} \lambda_x - \frac{3\lambda(\lambda-\kappa)^2}{\kappa} \kappa_x\right] \kappa_{xxx} \\ & - \frac{\lambda(\lambda-\kappa)^3}{\kappa^3} \kappa_{xx} + \left[\frac{2\lambda(\lambda-\kappa)^3}{\kappa^4} + \frac{3\lambda(\lambda-\kappa)^2}{\kappa^3}\right] \kappa_x^2 \\ & - \frac{(4\lambda-\kappa)(\lambda-\kappa)^2}{\kappa^3} \lambda_x \kappa_x \\ & + \tilde{A} \left[\frac{3(\lambda_x-\kappa_x)(4\kappa\lambda_x-7\lambda\kappa_x)}{(\lambda-\kappa)^2\kappa} - \frac{3\lambda(\lambda_{xx}-\kappa_{xx})}{(\lambda-\kappa)\kappa}\right] , \end{aligned} \qquad (3)$$

where $\tau = t/(3\mu R_T/\sigma)$. Thus, time, t, is made dimensionless with the film viscosity, μ, the surface tension of the film, σ, and the unconstricted tube radius, R_T. Also, $\tilde{A} = A/(\sigma R_T^2)$ is a dimensionless measure of the conjoining or disjoining forces.

The evolution equation is first order in time and fourth order in axial position. The initial condition is the initial film profile, which is arbitrary. The four boundary conditions are zero slope and constant film thickness imposed a long distance away from the constriction, and the symmetry conditions of zero slope and zero third derivative imposed at the pore neck.

The evolution equatin was solved numerically by descritizing the axial derivatives with Galerkin finite elements, and integrating in time with an adaptive Crank-Nicholson method.

Results

Results have been obtained for a series of initial film profiles (Gauglitz, 1985). We report primarily on results obtained for films with a uniform initial thickness, but one example of a nonuniform initial film is mentioned. Results focus on the effect of the initial film thickness because of its strong influence on the time to breakup. The results without thin-film forces will be discussed first, then the effects of conjoining and disjoining pressures are included.

A sequence of profiles is shown in Fig. 2 for a uniform initial film of thickness $H_o/R_T = 0.0124$. The first profile at $\tau = 1500$, shows the initial film growing thicker at the pore neck as liquid collects into a collar. In the second and third profiles, where the collar becomes large, local thinning at the sides is noticeable. The collar grows at increasing rate as it becomes larger, with breakup occurring at $\tau_b = 5496$, which is soon after the profile in Fig. 2 at $\tau = 5300$ (i.e., breakup is defined as the time when the collar reaches the tube centerline).

The effect of the initial film thickness on time to breakup, without thin-film forces, is summarized in Fig. 5 by the dotted line labeled by $\tilde{A} = 0$.

Time to breakup increases rapidly for thinner initial films due to the cubic dependence of the flow in the film on the film thickness.

When the initial film is nonuniform, the qualitative nature of the breakup can be different. A most interesting result occurs when the initial film is thick at the sides of the pore and thin at the center, as shown in Fig. 3. A series of film profiles for the thick-thin initial film is shown in Fig. 4. Two collars of liquid are observed to collect away from the pore neck, rather than one at the midplane of the pore constriction which occurred for the uniform initial films. As shown in Fig. 4, these collars translate towards the neck of the constriction as they become larger. For this initial film thickness, the two collars block the pore before they meet at the neck. In thinner thick-thin initial films, the two collars meet at the pore neck, and combine to form a single collar that grows and subsequently blocks the pore.

The formation of the collars at the sides of the pore neck arises from the strong dependence of the local film thickness on the flow rate in the film. Since the film is initially thick at the sides, liquid flows easily towards the constriction. However, the film is thinnest at the midplane, and, accordingly, liquid does not readily flow into the pore neck. The result is two collars of liquid that collect at the sides of the pore constriction, and then translate as humps towards the pore neck.

The effect of thin-film forces and initial film thickness on the time to breakup for uniform initial films is summarized in Fig. 5. Results are shown for both positive (disjoining forces) and negative (conjoining forces), values of the thin-film coefficient, $\tilde{A}$. With a scaling coefficient of $A = 10^{-21}$J and a surface tension of 30 mN/m, the results shown in Fig. 5 for $\tilde{A} = \pm 3.33\times10^{-8}$ and $\tilde{A} = \pm 1.33\times10^{-9}$ represent capillaries with unconstricted radii of 1 μm amd

5 μm, respectively. As expected, the thin-film forces become important in the 1 μm tube at a larger initial film thickness than in the 5 μm tube.

For a negative thin-film coefficient or conjoining pressures, the film interface is pulled towards the pore wall. The time to breakup decreases relative to that with $\tilde{A} = 0$ because the conjoining effect causes thinning of the film at the sides of the constriction and pushes the liquid into the pore neck. Conversely, for a positive thin-film coefficient, or a disjoining pressure, the film interface is repelled from the pore wall. The time to breakup increases as shown in Fig. 5; for sufficiently thin films, breakup never occurs. Although a collar of liquid initially grows at the pore neck for all initial film thicknesses, the disjoining force, in sufficiently small pores, does not allow the film to thin at the sides of the constriction. Hence, the collar cannot obtain enough liquid to block the pore, and breakup does not occur.

Movies of thin-film breakup in a constricted pore with a 0.1-cm radius were obtained with a Bolex movie camera. The initial film thickness was varied by driving a gas bubble, which leaves behind a film of liquid, through the constriction over a wide range of velocities. The time to breakup was obtained by viewing the movies frame by frame. The initial thickness of the film was calculated from the bubble velocity (Brethreton, 1961; Park and Homsy, 1984). Calculated time to breakup agrees qualitatively with the experimental results.

Acknowledgment

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Notation

A = coefficient in Eqn. (2), J

H = film thickness, m

H_o = initial film thickness, m

$\tilde{r}$ = dimensionless radial position

R_T = unconstricted tube radius, m

t = time, s

$\tilde{x}$ = dimensionless axial position

Greek Letters

κ = reduced radial position of the film interface

λ = reduced radial position of the tube wall

μ = viscosity of the liquid film, mPa·s

Π = conjoining/disjoining pressure, Pa

σ = interfacial tension, mN/m

τ = dimensionless time

Subscripts

x = denotes partial derivative with respect to the reduced axial position

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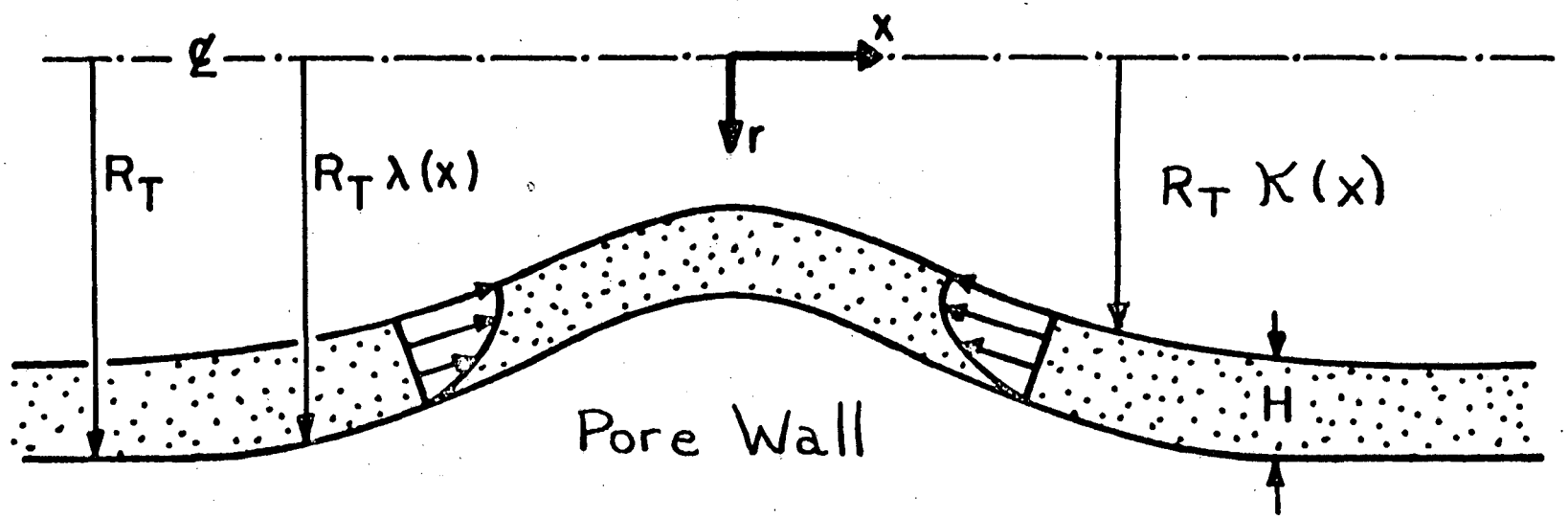

Figure 1 Thin film of viscous fluid inside a constricted capillary.

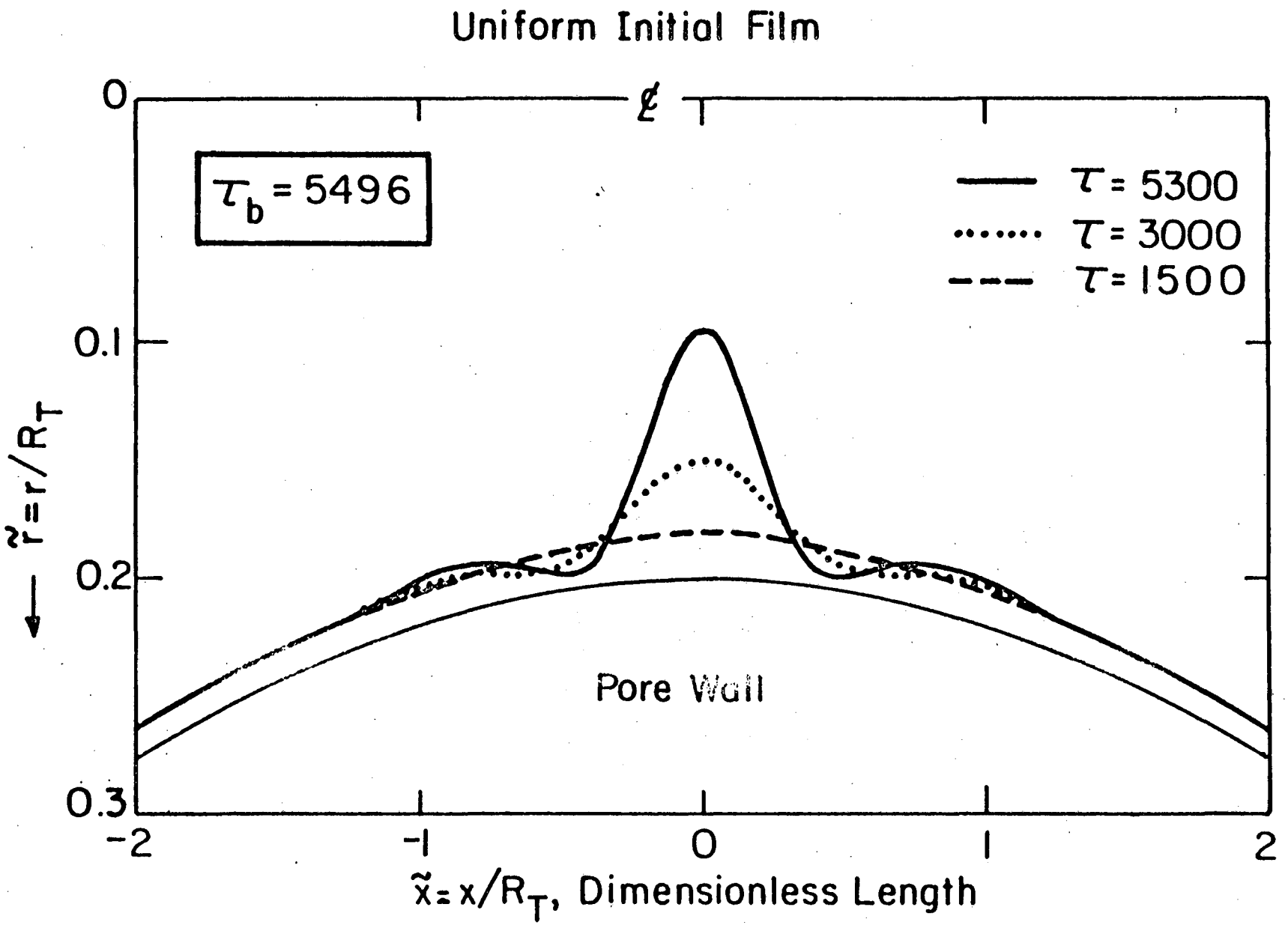

Figure 2 Thin-film evolution for a uniform initial film of thickness, $H_o/R_T = 0.0124$.

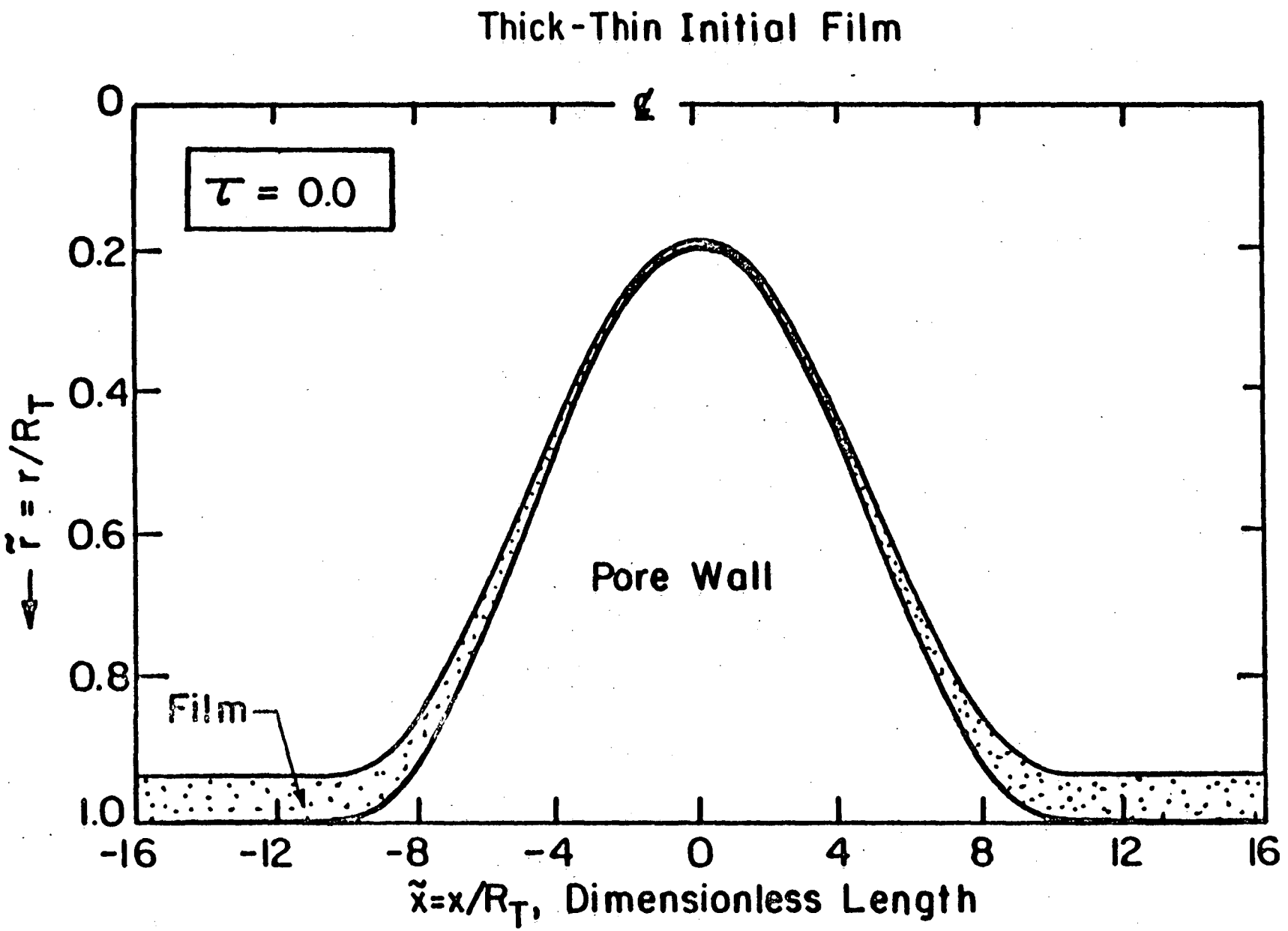

Figure 3 Thin-film evolution for a thick-thin initial film. The profile shown is the initial condition.

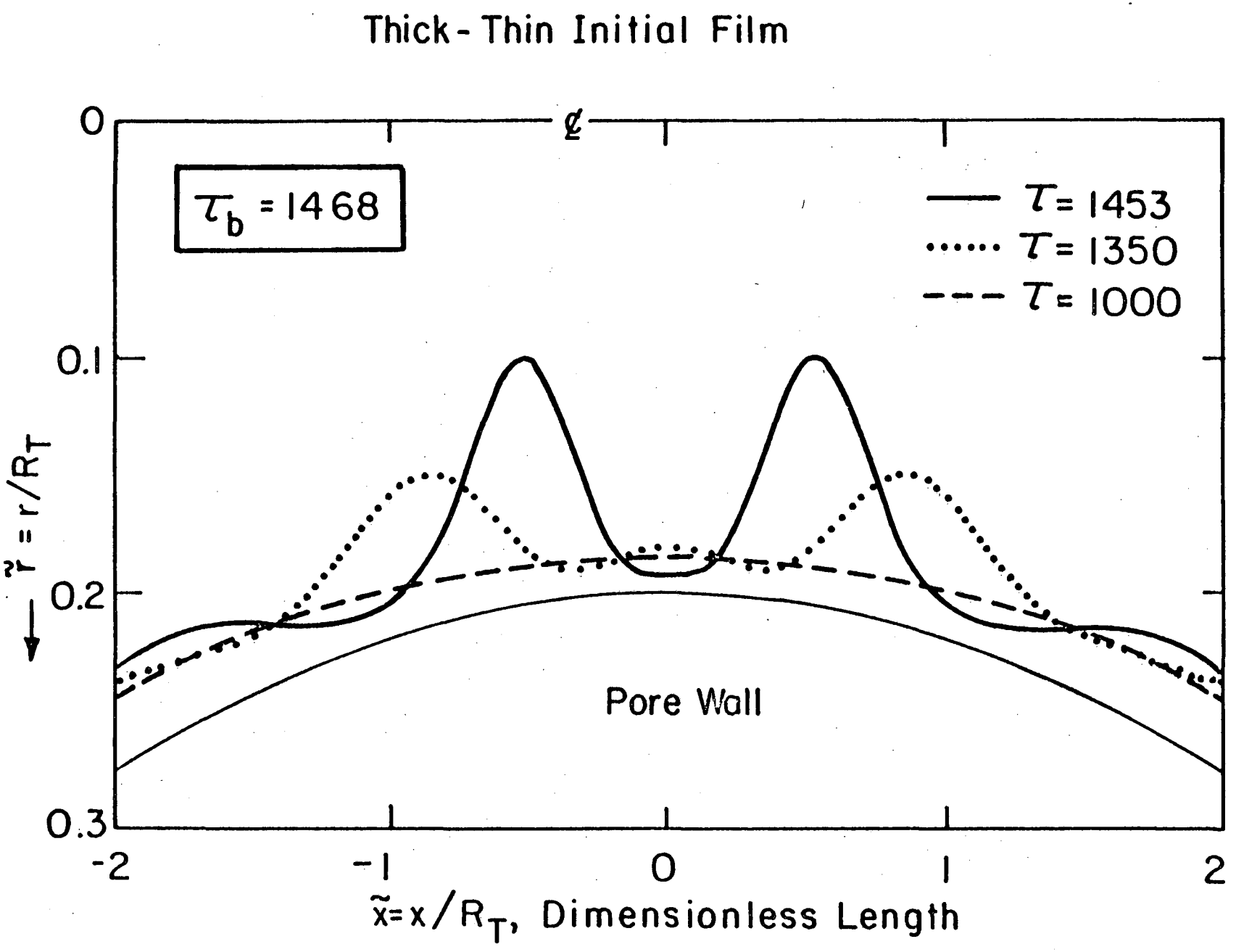

Figure 4 Thin-film evolution for a thick-thin initial film.

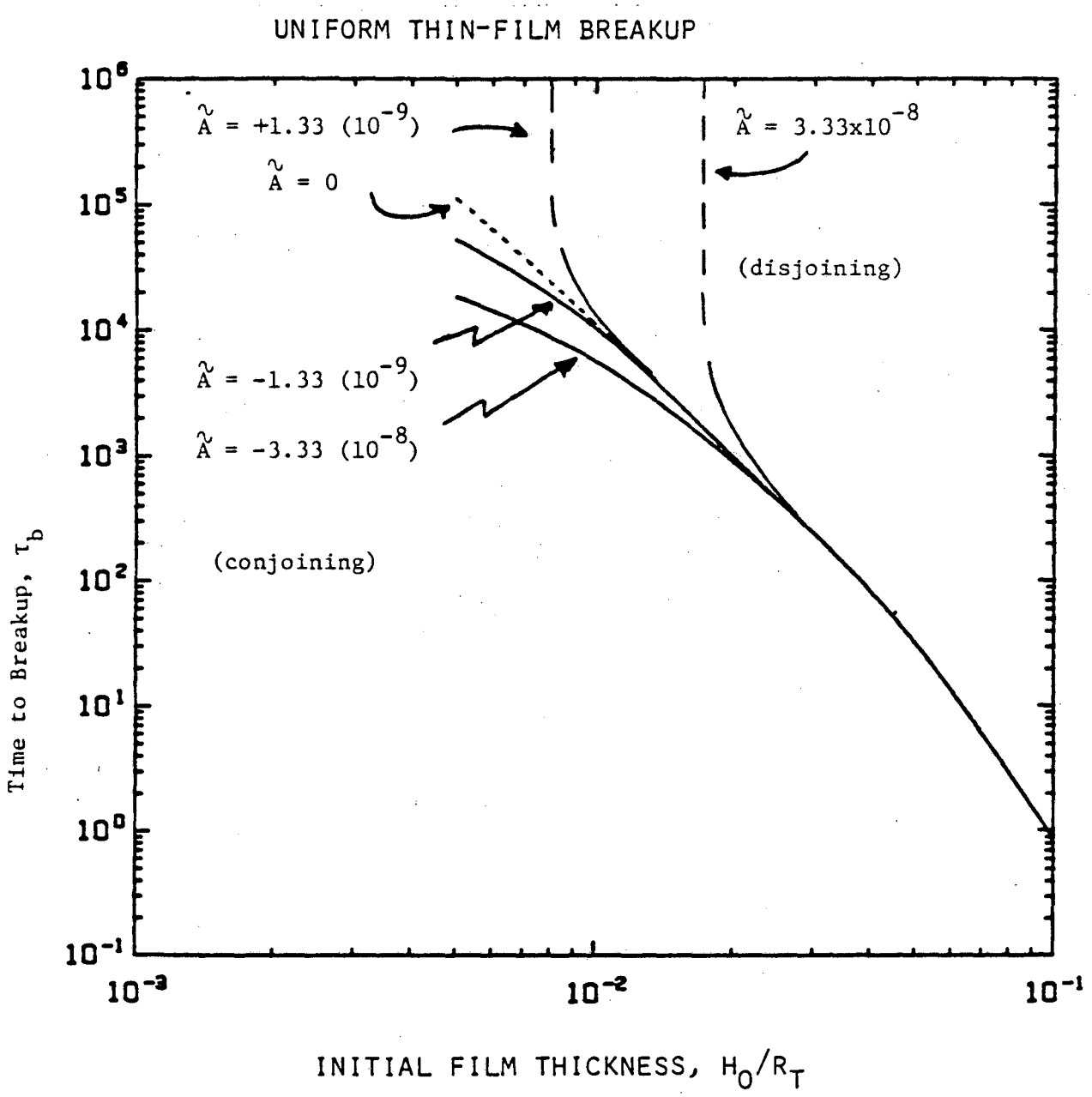

Figure 5 Effect of initial film thickness H_o/R_T and conjoining/disjoining pressures, as parameterized by $\tilde{A}$, on the time to breakup.

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