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POSSIBLE EFFECTS OF SHEET PORE SIZE AND THERMODYNAMIC PRESSURE ON BOILING HEAT TRANSFER MECHANISMS IN IMPULSE DRYING

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ABSTRACT

A fundamental study of boiling in the presence of fibrous beds was conducted to gain insight into impulse drying, a novel technique which employs phase-change heat transfer to dry a wet paper web. The results indicate that bed pore size and system pressure are significant factors in controlling boiling heat transfer. The model fiber beds are composed of ceramic fibers having diameters of 3.0 μm, 8.4 μm, or 18.5 μm, and have porosities which range from 0.93 to 0.95. At surface temperatures that exceed the system saturation temperature by more than approximately 25°C, heat flux is controlled by the rate at which the fibrous bed supplies water to the heater surface by capillary forces, and hence, is directly proportional to pore size of the bed. Similarly, the heat flux is found to increase significantly at pressure levels lower than what is likely to exist within the sheet during impulse drying. These results suggest interesting roles for pore size and pressure within the sheet during impulse drying. Coupled with previously-reported evidence for boiling heat transfer mechanisms during impulse drying, the high heat fluxes measured during impulse drying are postulated to result in part from the effect of pressure on boiling phenomena in the fibrous sheet. Moreover, the magnitude of heat flux sustained in the latter half of an impulse drying event probably depends on the pore size distribution of the sheet, as this controls the flow rate of water to the plane of evaporation within the sheet. Pressure may aid in maximizing the water supply rate by maintaining high levels of saturation within the sheet by increasing vapor density.

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INTRODUCTION

Since the early 1970's, a number of factors have motivated efforts to improve dewatering capabilities in the papermaking process. Although significant improvements have been attained, the basic mechanisms of conventional techniques limit the potential for further major improvements. Dramatic improvements can now be best achieved through novel processes involving fundamentally different mechanisms. Impulse drying is one such process that has been under development at The Institute of Paper Chemistry since the early 1980's.

Impulse drying combines the wet pressing and drying operations into a brief event pressing the moist sheet in a nip formed by a felt-covered, unheated roll or shoe and an externally-heated roll, as illustrated in Figure 1. The impulse dryer is designed to be situated between a conventional press section and a shortened conventional dryer section. Heat flux data for a typical impulse drying event with linerboard are illustrated in Figure 2. Heat transferred to the moist web of paper peaks at instantaneous heat fluxes on the order of 3.0 MW/m^2 as the temperature of the heated metal surface drops by about 25°C . By integrating the instantaneous heat flux curve, the average heat flow to the sheet is determined to be on the order of 60 kJ/m^2, which is much higher than heat transferred during conventional drying.

Initial studies of impulse drying demonstrated the ability of the process to generate drying rates on the order of 30,000 kg/(hr-m^2) [1], yielding sheet solids contents prior to the drier section ranging from 55 to 70%. Because dewatering rates achieved with conventional pressing and drying techniques are appreciably lower, impulse drying presents opportunities to reduce energy consumption, and also to reduce the capital costs associated with conventional drying equipment.

The dramatic increases in heat flux and water removal rate experienced with impulse drying suggest that the mechanisms that control dewatering differ significantly from those of conventional pressing and drying operations. The high water removal rates for impulse drying result from the combined effects of volume reduction due to wet pressing and bulk flow of water,

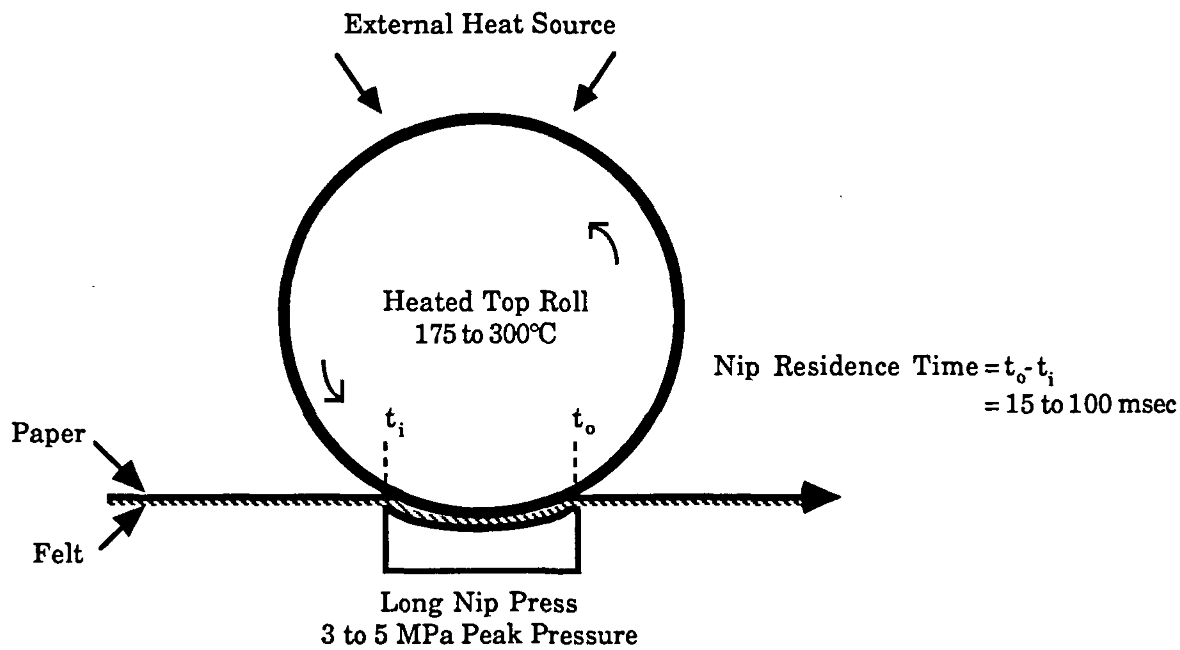

Figure 1. Implementation of the impulse drying process.

presumably under the influence of a pressure gradient generated by vapor formation [2]. As illustrated in Figure 3, this additional mechanism of bulk flow of water yields outgoing solids contents that are much higher than those for wet pressing over a range of sheet moisture contents. While exiting sheet solids content for a conventional pressing arrangement is limited to about 45% solids, impulse drying can achieve significantly higher exiting solids contents. Moreover, impulse drying also effects some degree of dewatering on sheets that are at solids contents well beyond the range of wet pressing.

Some portion of the water removed from the sheet during impulse drying occurs in vapor form. As illustrated in Figure 4, the relative distribution of the water phases depends on the initial moisture content of the sheet [3]. As hypothesized, dewatering due to volume reduction is augmented by vapor generation, as the vapor pressure gradient presumably acts as a driving force for bulk liquid removal.

These pieces of evidence suggest that boiling may contribute to heat transfer during the impulse drying event. Boiling is one mode of heat transfer that generates the magnitude of heat

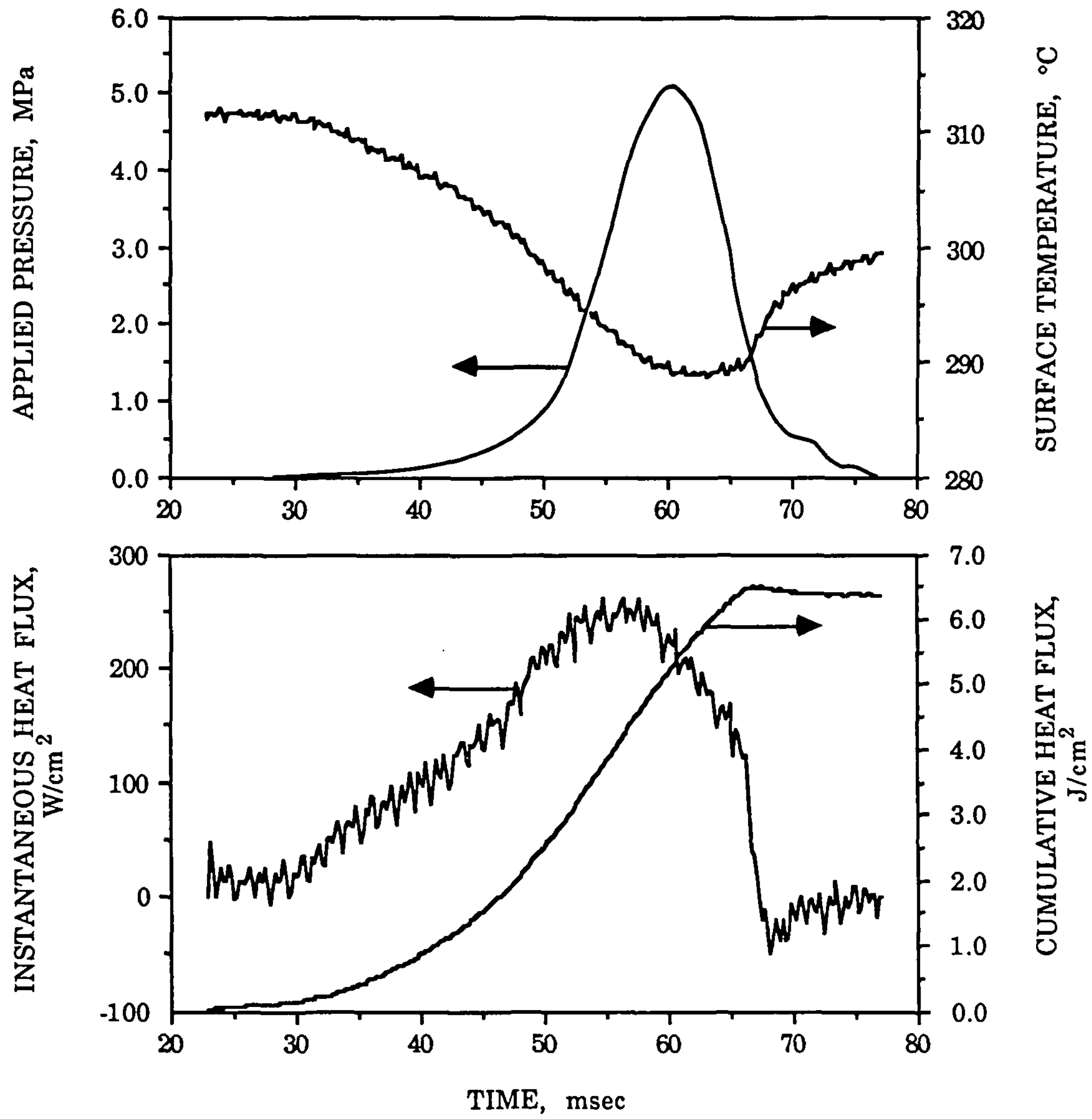

Figure 2. Data for a typical impulse drying event.

flux demonstrated in impulse drying, and the generation of a vapor phase within the sheet requires a phase change mechanism. The occurrence of boiling within the fiber sheet in the short time frame of an impulse drying event presents a complex engineering problem. Interacting issues of sheet compressibility, multiphase flow through porous media, thermodynamics, and boiling heat transfer compose a problem of enormous complexity. This paper addresses one facet by investigating fundamental principles involved with boiling in a fibrous bed. Understanding this model boiling process may provide insight regarding boiling heat transfer in impulse drying.

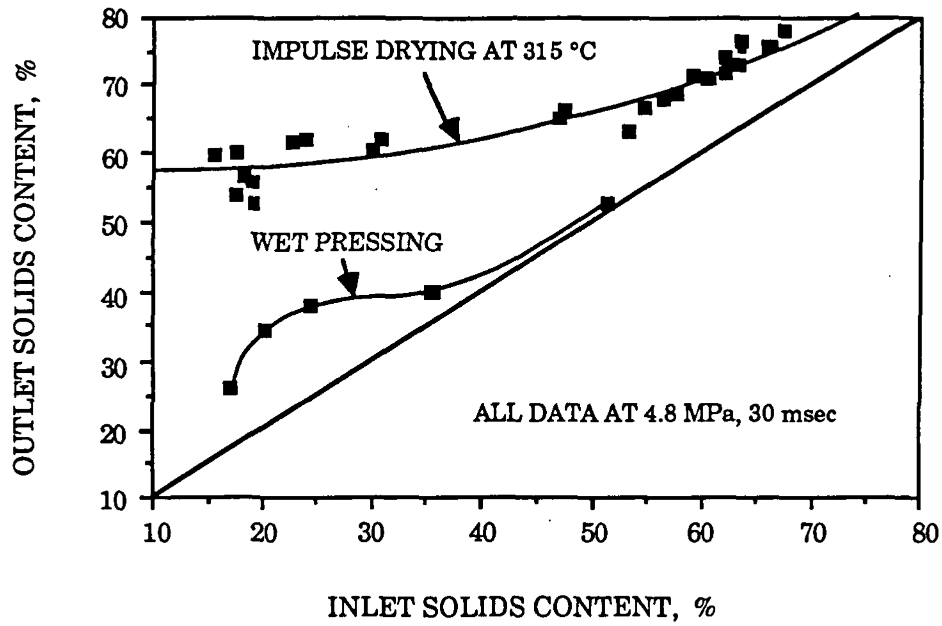

Figure 3. A comparison of dewatering capabilities for conventional wet pressing and impulse drying for a 125 g/m² linerboard sheet.

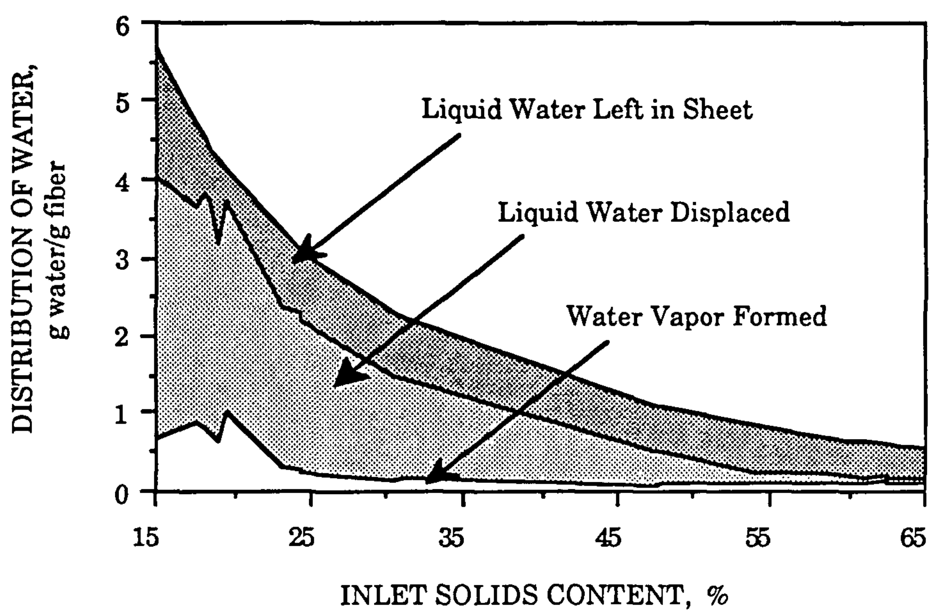

Figure 4. The redistribution of water during an impulse drying event.

EXPERIMENTAL APPARATUS

Mechanistic studies of boiling phenomena begin with determination of the characteristic boiling curve, which is the relationship between heat flux and wall superheat (the difference between the heater surface temperature and the system saturation temperature). The experimental apparatus designed to gather data for boiling in a fibrous medium, illustrated in Figure 5, is composed of four systems: the boiling cell, the heat supply system, the data acquisition system, and the process control system [4]. The apparatus is designed to study heating block surface temperatures up to 400°C and cell pressures ranging from 0.10 to 0.28 MPa. The beds are composed of ceramic fibers with diameters of 3.0, 8.4, or 18.5 μm. Bed porosity ranges from 0.93 to 0.96, permeability ranges from 10^{-11} to 10^{-9} m^2, and average pore diameter (as determined from capillary pressure functions [5,6]) ranges from 30 to 250 μm.

The boiling cell consists of a 9-cm ID x 110-cm long machined quartz cylinder that houses the fiber bed. The fiber bed is formed in one end of the tube by filtration from a slurry having a consistency of approximately 0.1%. After formation, up to six fine-gage thermocouples are embedded within the fiber bed to gather information about thermal patterns that develop as the boiling process proceeds. The tube is axially compressed between the heating block and a top mounting plate to seal the system for pressurized boiling.

The heating block, which is machined from a copper-tellurium alloy (ASTM B145), is 17.8 cm in length by 10.2 cm in diameter. Three thermocouples embedded within the block proximate to the boiling surface measure the temperatures necessary to determine surface temperature and heat flux. Surface temperature is calculated rather than measured because any surface nonuniformity (such as that caused by the presence of a surface thermocouple) significantly disrupts the character of the boiling process. Because the thermal conductivity of the copper material varies significantly over the experimental temperature range, heat flux is determined from the one-dimensional heat diffusion equation incorporating the curve-fitted expression for temperature-dependent thermal conductivity. To ensure one-dimensional heat flow, convective heat losses are minimized by

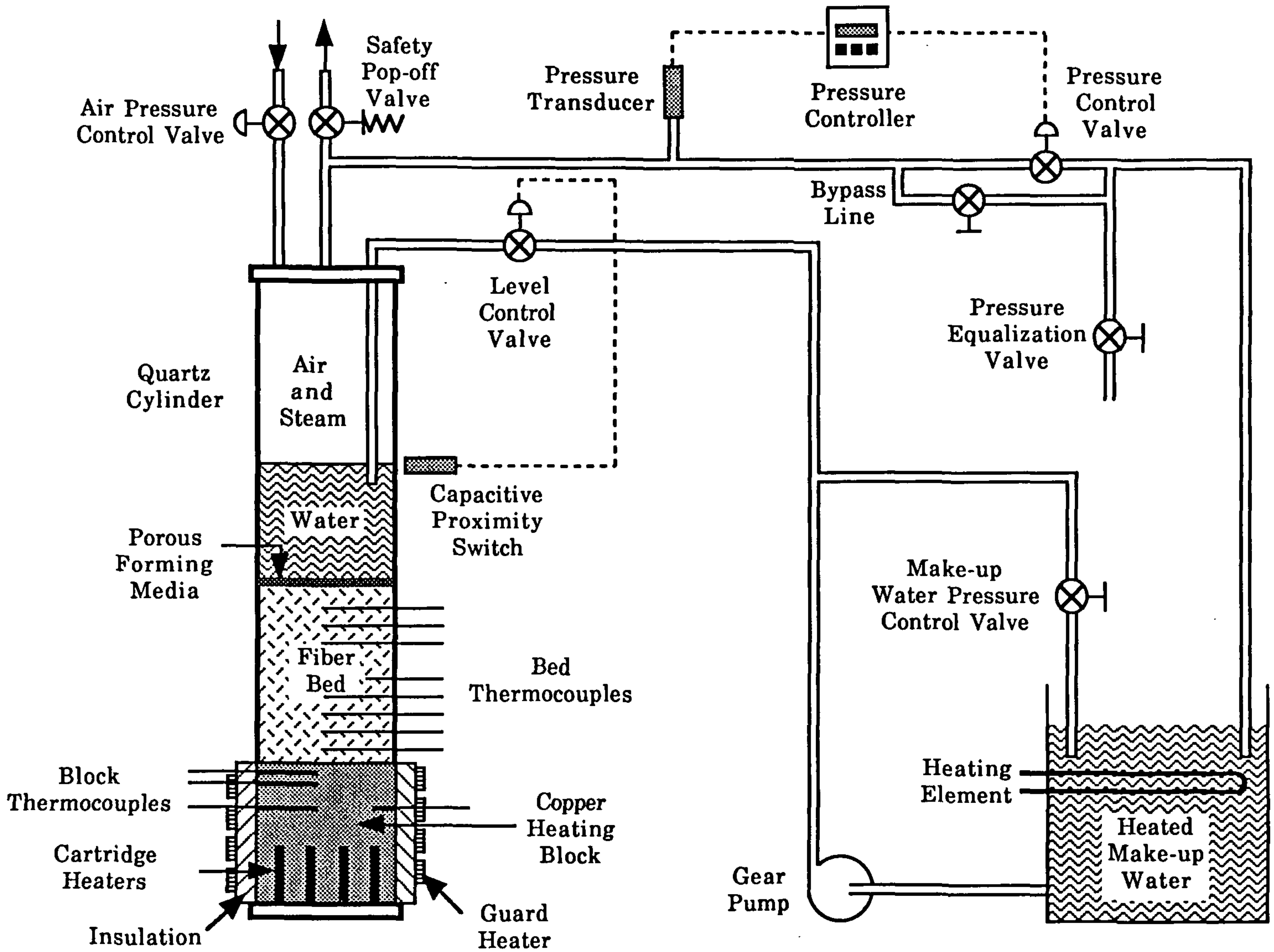

Figure 5. Schematic of the boiling cell apparatus.

wrapping the heating block with 4.5-cm thick $CaSiO_4$ insulation, and by wrapping the insulation with a guard heater. Nine cartridge heaters positioned symmetrically in a vertical orientation in the bottom of the heating block provide the heat for boiling. A silicon-controlled rectifier (SCR) meters electrical current to the heaters based on the output signal from the temperature controller.

A number of Type-K thermocouples and one strain-gage pressure transducer are interfaced with a data acquisition system, which consists of a high speed A/D I/O board mounted on the motherboard of an AT-compatible computer, two daisy-chained expansion submultiplexer boards which are equipped with cold-junction compensation circuitry to reference the thermocouple voltages, and a universal terminal board.

The experimental control system developed for this apparatus provides data acquisition, heater block surface temperature control, and system pressure control. The temperature of the boiling surface of the copper heating block is continuously calculated by software that reads the analog signals from the block thermocouples via the data acquisition equipment. This value is downloaded as the process input to the PID temperature controller, which actuates the SCR. A pressure transducer located on the vapor vent line feeds a signal to a PID controller, which actuates the pneumatic valve on the vapor vent line to control system pressure. Water level in the cell is controlled by interfacing a capacitive proximity switch with a normally-open solenoid valve to meter flow of heated make-up water, and does not interact with the other components of the control system.

RESULTS AND DISCUSSION

Boiling experiments in fibrous media have been executed to determine the effects of medium pore diameter and system pressure on the characteristic boiling curve. Based on the additive uncertainty model, uncertainty for calculated heat flux is 0.9 W/cm^2, and for calculated surface temperature is 0.6°C. Though the maximum pressure of 0.28 MPa used in this study is probably much lower than levels that develop within the cellulose fiber sheet during impulse drying, boiling at higher pressures was not attempted due to a catastrophic failure of the boiling cell at elevated temperatures at 0.28 MPa. The reader is cautioned that the data comparisons to be presented are only intended to illustrate trends effected by experimental parameters. Because data to be compared have similar (but not identical) average pore diameters and bed heights, the data should not be interpreted for absolute magnitudes of parametric effects.

Figure 6 illustrates the boiling phenomena that occur during boiling in a fibrous medium. Vapor generated at the heater surface rises under the influence of a partial pressure gradient and buoyant forces, and liquid flows down to the heater surface under the influence of capillary forces and gravity. This two-phase zone of counterpercolating vapor and liquid is nearly isothermal, and grows in height with heat flux. The vapor condenses at the interface of this zone and the overlying liquid-saturated zone. If the height of this zone grows to encompass the entire bed, then the vapor protrudes from the top of the bed and agitates the overlying pool of liquid. In the case of Figure 6, the entire bed height of 25 cm is engulfed in two-phase flow!

The nature of boiling is modified by the presence of the fibrous bed, as illustrated in Figure 7 (only the nucleate regime of the pool boiling curve for water is presented). The boiling curve for the fibrous bed exhibits two boiling regimes and a point of transition between them that represents the peak heat flux attained during the experiment. The direct dependence of heat flux on wall superheat in the initial regime is similar to the nucleate pool boiling regime. Heat transfer is limited by the ability of the heater to supply heat to the boiling surface, which is related to nucleation characteristics of the heater surface. Apparently, some form of active nucleation is occurring at voids on the heater surface. While completion of a full bubble growth cycle is unlikely, the initiation of bubble growth is certain to proceed within limits posed by physical constraints of the pore structure. Physical inhibition of nucleation may account for the reduced nucleate boiling effectiveness demonstrated with the fibrous medium. It is during this nucleate-type regime that the isothermal, two-phase counterpercolation zone develops.

In the second regime, the heat flux is totally independent of wall superheat. Here, heat flux is

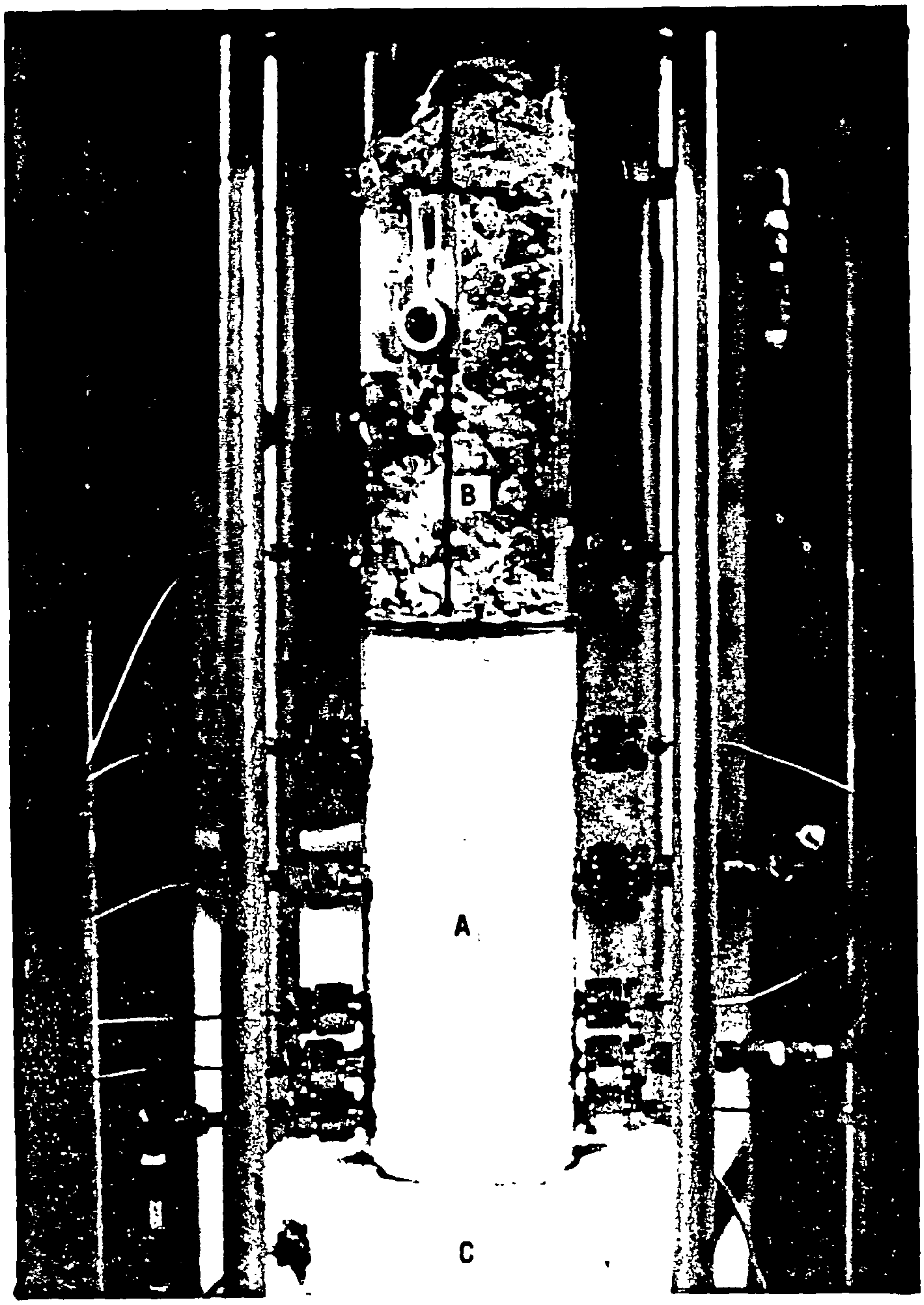

Figure 6. Photograph of boiling in a 25-cm high fibrous bed having an average pore diameter of 250 μm. A = fibrous bed, B = insulated heating block, C = overlying pool of liquid water.

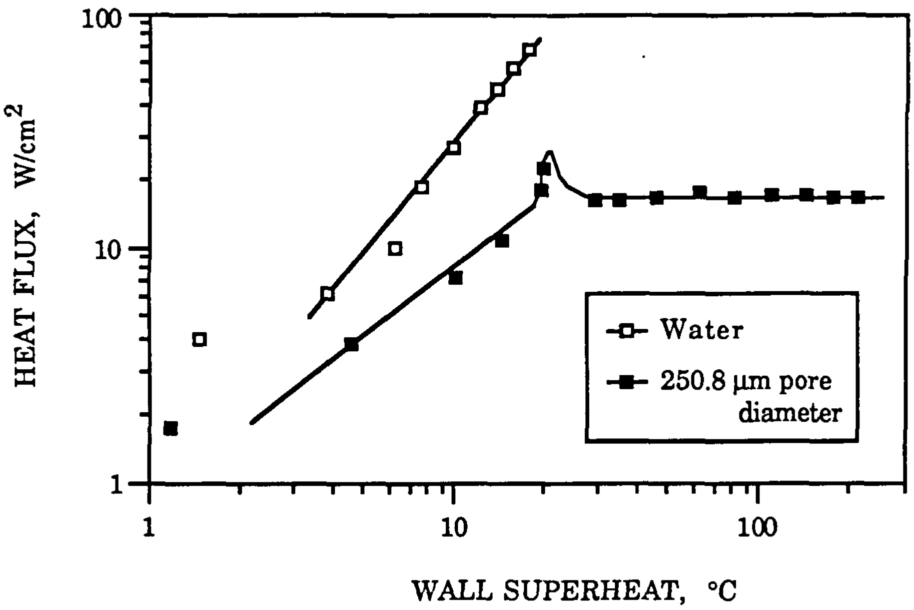

Figure 7. Typical boiling curves measured with the boiling cell apparatus.

controlled by the rate of liquid flow to the heater surface under the influence of capillary forces of the bed. This obviously depends on the saturation level and pore size distribution of the bed. The development of a vapor film on the heater surface in this regime is unlikely because the inertial force of the liquid flowing to the surface would break through the film, which would have a maximum thickness on the order of a couple hundred microns. Consequently, some degree of liquid/surface contact is likely to occur throughout this regime, which means that phase change may occur by nucleation throughout the entire boiling curve.

The point of transition between the two regimes, called the critical heat flux (CHF), is a potentially unstable condition that requires prompt action by the surface temperature control system. The beds with average pore diameters greater than 220 μm exhibit a peak heat flux with a magnitude greater than that of the iso-heat flux regime. The phenomena associated with this peak are experimentally observed to be very sensitive: more scatter is apparent in the thermocouple readings as the process approaches the CHF. At the CHF, these beds experience a dramatic change in the fluid flow phenomena that reduces the heat-absorbing capacity of the bed. Attempts to increase surface temperature beyond the CHF yield an instantaneous, rapid rise in surface temperature (typically, an increase of 10 to 15°C in a period of 10 to 15 seconds) until the control system arrests the rise. Frequently, the process must be returned to a lower temperature, as the rise often overshoots the controller's setpoint.

Saturation is undoubtedly a major factor in controlling heat flux, particularly in the iso-heat-flux regime. The saturation profile, and not necessarily the overall magnitude of saturation, is important because the supply of liquid at the heater surface will depend on the quantity available in the bed very near to the heater surface. The profile is likely to exhibit a maximum saturation near the top of the bed and a minimum saturation near the heater surface, with an exponential increase from bottom to top.

The observation of a peak heat flux and subsequent decline to the iso-heat-flux regime for beds of large average pore diameter may be related to the saturation profile. This decline is postulated to be caused by a reduction in the ability of the bed to supply water to the heater surface. Since the pore structure of the rigid bed is unchanged, something must happen to change the saturation profile in the bed at the CHF. Due to volume expansion upon phase-change, the velocity of vapor in the flow channels is likely to be much higher than that of liquid. In a manner analogous to the Helmholtz instability at the interface of two immiscible fluids, the vapor velocity in the flow channels may reach a critical level that effects a change in the relative distribution of water and vapor phases within the bed.

THE EFFECT OF AVERAGE PORE DIAMETER

Many of the phenomena experienced in boiling in a fibrous bed depend on the average pore diameter of the bed, as illustrated in Figure 8. The slope of the nucleate-type regime decreases as pore diameter decreases, most probably because of the effects on the hydrodynamics of the vapor phase. First, vapor generation involved with nucleation is probably inhibited in direct proportion to the average pore diameter, which defines the physical space that the vapor phase can grow into. Second, the resistance to vapor flow away from the heater surface increases in direct proportion to the

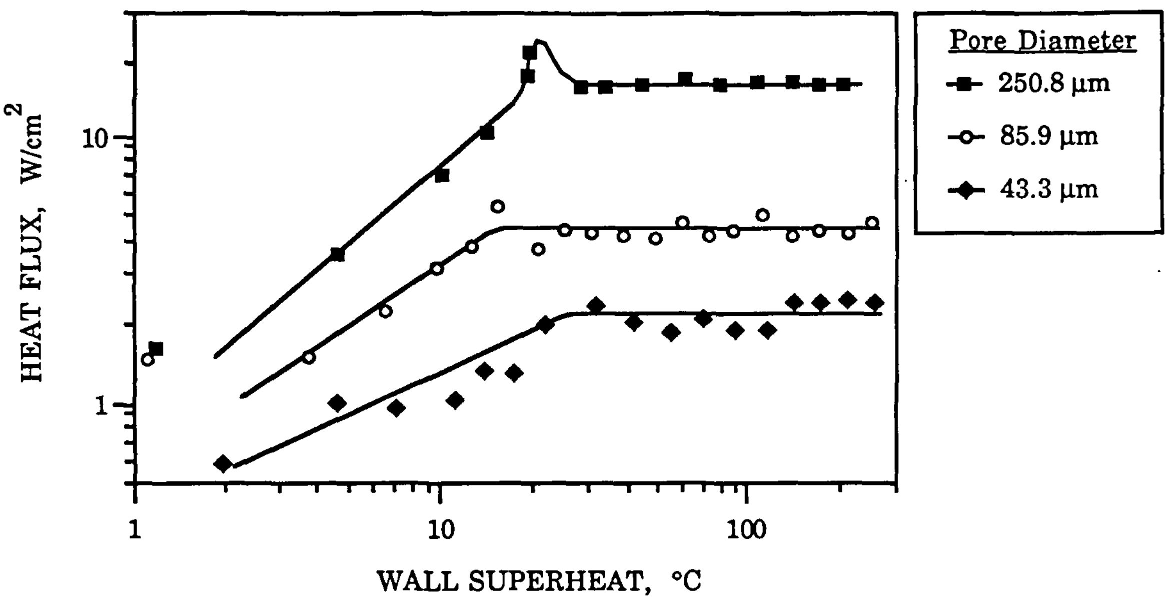

Figure 8. The effect of average pore diameter of the bed on the boiling curve.

diameters of the flow channels. Any accumulation of vapor at the surface will increase the resistance to heat transfer at the surface. Thus, these two factors interact to reduce the heat transfer coefficient in the nucleate regime.

Behavior at the CHF is affected by the average pore diameter of the bed, as well. Each of the boiling curves for the large average-pore-diameter beds (220 to 260 μm) exhibits a distinct peak in heat flux between the two regimes, and an associated rapid escalation in surface temperature. However, none of the small average-pore-diameter beds (35 to 90 μm) exhibits either of these phenomena. Rather, a smooth transition from the nucleate-type regime to the iso-heat-flux regime is experienced. This difference in behavior at the CHF may be related to the curvature of the saturation profile in the bed. Regardless of transition phenomena, all experiments at 0.10 MPa exhibit transition at a wall superheat of about 20°C.

The magnitude of heat flux in the iso-heat-flux regime is directly related to average pore diameter. As illustrated by Washburn's equation for the rate at which a liquid rises in a capillary,

$$v = \frac{dh}{dt} = \frac{r^2}{8\mu h}\left[\frac{2\sigma\cos\beta}{r} - \rho g h\right] , \qquad (1)$$

the rate of liquid supply to the surface depends on the diameter of the pores. Accordingly, as the pore diameter decreases, the rate of water supply, and hence, the heat flux, decreases.

The data for the smallest average pore diameter in Figure 8 exhibits a fair amount of scatter for two reasons. First, utilizing a log ordinate axis amplifies the scatter of these data because of broadening of the scale in the 0.8 to 2.0 W/cm^2 range. Second, the temperature difference between the two thermocouples used to calculate heat flux is approaching the same order of magnitude as the precision in thermocouple readings. Consequently, the uncertainty for this set of data is higher than those for larger average pore diameters.

THE EFFECT OF SYSTEM PRESSURE

Figure 9 illustrates the effect of system pressure on the boiling curves for fibrous beds with average pore diameters of approximately 250 μm. Prior to the region of transition, the nucleate-type regime is insensitive to pressure in the studied range. Because classical pool boiling studies with water indicate significant changes in the nucleate regime at pressures of 0.34 MPa [7,8], this observation suggests that geometric constraints of the pore structure dominate pressure effects in controlling phase change, and consequently heat transfer. It is interesting to note that although bed saturation is higher due to the increased vapor phase density at elevated pressures, heat flux in the nucleate-type regime below wall superheats of about 20°C does not increase. This also suggests that geometric constraints dominate pressure effects in controlling nucleation. The nucleate-type regimes for beds with average pore diameters less than 90 μm also do not appear to be affected by pressure.

For beds with large average pore diameters, process instability at the CHF is exacerbated as the system pressure increases. Under pressure, system stability as the process nears the CHF is

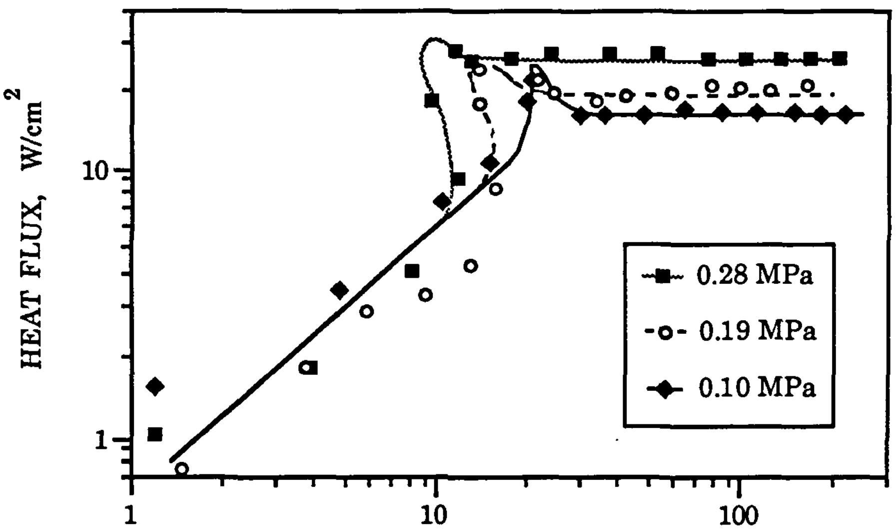

Figure 9. The effect of system pressure on the boiling curve.

attained with increasing difficulty. At some point, the heretofore-experienced direct relationship between wall superheat and heat flux reverses, as the wall superheat actually decreases as higher heat fluxes are approached. This is exhibited as a backward bend in the boiling curve, until finally, the heat flux peaks and the surface temperature rapidly escalates. The behavior of decreasing wall superheat at increased levels of heat flux just prior to the critical is reproduced in all of the pressurized boiling runs for beds with average pore diameters above about 220 µm. The wall superheat at the CHF is inversely proportional to pressure, which agrees with the trend observed in classical pool boiling.

The effect of pressure on the magnitude of heat flux in the iso-heat-flux regime is in part due to the increased density of the vapor phase. The consequent increase in bed saturation results in greater liquid water supply to the heater surface, which increases the heat-absorbing capacity of the bed. For all average pore diameters, the magnitude of the iso-heat-flux regime under pressure is greater than that for atmospheric conditions.

IMPLICATIONS FOR IMPULSE DRYING

The results of this boiling research provide insight into the contribution of sheet pore size and internal pressure in controlling heat transfer to the sheet during impulse drying. Data collected by Lavery [3] indicate some interesting phenomena as the impulse drying event is extended. As illustrated in Figure 10, three superimposed events of different nip residence times track each other very closely throughout the event. After the rapid initial rise to the peak heat flux, the heat flux decays to a lower value. In the case of a short event, the decay is rapid, but in the case of an extended event, the heat flux decays exponentially, and nearly asymptotes at about 75 W/cm^2 until nip pressure is relieved. During this latter portion of the extended event, the phenomena within the sheet approach a quasi-steady state.

Based on the results of this investigation, the latter portion of the extended impulse drying event may be controlled by an interaction of sheet pore size, pressure buildup within the sheet, and counterpercolation of steam and liquid water within the sheet. In the iso-heat-flux regime, the characteristic curves for boiling in fibrous media demonstrate that heat flux is independent of thermal driving force, and depends on the pore size of the media and its ability to deliver liquid to the heater surface, and also on the system pressure. By the time the quasi-steady regime in the impulse drying event occurs, free water at the heater surface is likely depleted, and the plane of evaporation probably is located within the sheet structure. At this point, heat flux will be controlled by the rate at which the pore structure of the sheet can supply liquid water to the plane of evaporation for phase change. As with the model fibrous bed, a nearly isothermal zone, however thin, exhibiting counterpercolation of steam and liquid water delivers liquid to and vents vapor from the plane of evaporation. Thus, the heat flux will depend to a large degree on the pore structure of the sheet in this regime. The slight decrease in this regime's heat flux evident in Figure 10 may be an indication of continued sheet compression and resultant decrease in pore size of the sheet, leading to a decrease in liquid flow rate.

The difference in magnitudes of heat flux between the iso-heat-flux regime of steady-state boiling in fibrous media and the quasi-steady regime of an extended impulse drying event may be bridged by the role of pressure. The highest heat flux in fibrous media boiling of about 25 W/cm^2 is

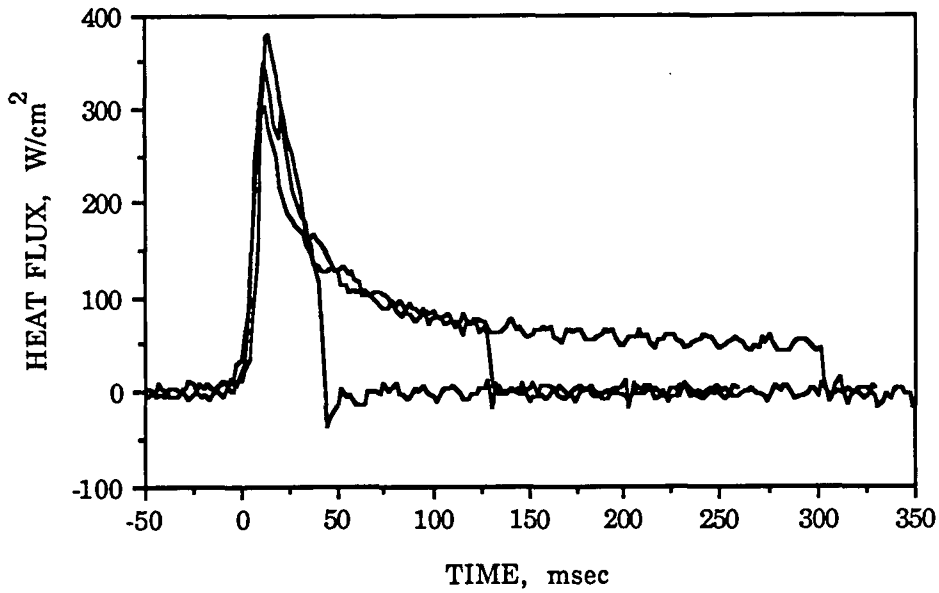

Figure 10. Behavior of instantaneous heat flux during impulse extended drying events for a 125 g/m² linerboard sheet initially at 40% solids presteamed to 180°C. Nip conditions are a peak pressure of 3.4 MPa and a hot surface temperature of 315°C.

obtained at 0.28 MPa. Internal sheet temperatures experienced of 150°C during impulse drying [9] indicate that thermodynamic pressures could be on the order of 1.25 MPa. If the trend of increasing magnitude of heat flux with pressure in the iso-heat-flux regime could be extrapolated to 1.25 MPa, values in the neighborhood of 75 W/cm² may be attainable.

These results also suggest that papermaking operations that reduce the average pore diameter of the sheet may be detrimental to impulse drying water removal. In general, impulse drying water removal rates are directly related to heat flux, which is the driving force for water removal by displacement due to growth of a vapor phase. Based on this research, heat flux may be directly related to pore diameter in the portion of the event where heat flux is limited by sheet structure. Thus, by reducing the sheet pore diameter, mechanical refining of the furnish reduces the driving force for water removal in the latter portion of the impulse drying event. Additionally, the structural changes in the fiber induced by refining increases its water-holding capability. The additive effects of increased difficulty of water removal and decreased driving force for water removal indicates that refining may reduce the potential for water removal in impulse drying.

CONCLUSIONS

Boiling in the presence of a fibrous porous medium possessing significant capillary forces exhibits interesting phenomena that differ significantly from the classical pool boiling phenomena. The characteristic curves for boiling in a fibrous bed exhibit two regimes. The first regime is similar to the nucleate regime of classical pool boiling in that heat flux is directly proportional to wall superheat. Heat transfer in this nucleate-type regime is controlled by nucleation characteristics of the heater surface, and physical space available for vapor growth. The heat flux of the second regime is constant and is, therefore, independent of wall superheat. Heat transfer in this iso-heat-flux regime is controlled by the rate at which the pores of the fibrous bed supply water to the heater surface.

The average pore diameter of the bed is an important factor for boiling in a fibrous medium. The slope of the nucleate-type regime, and the magnitude of heat flux in the iso-heat-flux regime, are directly proportional to the average pore diameter. The behavior at the point of transition between the two regimes appears to depend on a critical value of average pore diameter. Beds with average pore diameters above 220 μm exhibit a peak heat flux with an associated rapid rise in surface temperature, while beds with average pore diameters below 90 μm exhibit a smooth transition between the nucleate-type and iso-heat-flux regimes. System pressure apparently has no effect on the portion of the nucleate regime prior to the transition region. However, at elevated pressures, the instability exhibited by the large-pore-diameter beds at the CHF is exacerbated. The magnitude of heat flux in the iso-heat-flux regime increases with pressure as the decrease in density of the vapor phase yields higher levels of bed saturation.

Based on this research, sheet pore diameter would seem to be the factor limiting the heat flux in the quasi-steady portion of an extended impulse drying event, as the rate of water supply to absorb the heat at the interface of phase-change depends on pore size. The level of thermodynamic pressure within the sheet also controls heat flux due to its effect on sheet saturation.

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NOMENCLATURE

- g - gravitational acceleration
- h - height in capillary
- r - radius of capillary
- t - time
- v - velocity
- β - contact angle
- μ - viscosity
- ρ - density
- σ - surface tension

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