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# INSIGHTS INTO BOILING HEAT TRANSFER IN IMPULSE DRYING

G.R. RUDEMILLER AND J.D. LINDSAY

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G. Rudemiller and J. Lindsay

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# INSIGHTS INTO BOILING HEAT TRANSFER IN IMPULSE DRYING

Gary R. Rudemiller
Technical Assistant
Westvaco Corporation
Wickliffe, KY 42087

Jeffrey D. Lindsay
Assistant Professor
The Inst. of Paper Science and Tech.
Atlanta, GA 30318

## ABSTRACT

Heat transfer is known to be the source of the advantages and disadvantages of impulse drying. If impulse drying is to be commercialized, the heat transfer processes of impulse drying must be better understood and controlled. Unfortunately, fundamental information about intense phase-change heat transfer in fibrous media has been lacking. A study of boiling in fibrous media was thus undertaken. Steady-state boiling was examined in well-characterized fibrous beds comprised of ceramic fibers. The results showed that boiling in fibrous media can be substantially different from boiling in other systems. A constant heat-flux regime was observed, in which heat flux is limited by the flow rate of water toward the hot surface. While the details of the model system studied here differ greatly from impulse drying in real paper, some relevant conclusions can be drawn.

## INTRODUCTION

Impulse drying is a novel water removal process in which a moist sheet is briefly pressed with a hot roll at 250-375°C. One possible implementation is shown in Figure 1. In impulse drying, intense heat transfer interacts with other mechanisms to create a process that gives significantly higher dryness than wet pressing while using less energy than conventional cylinder drying (1). Commercialization has been hindered, however, by the problem of delamination: in some cases, vapor pressures generated in the sheet can cause a serious loss of z-directional strength or even catastrophic sheet failure (2).

The fundamental physics of impulse drying have been explored in a variety of studies. Burton (3,4) conducted dynamic *in-situ* measurements of sheet density, vapor pressure, and temperature during simulated impulse drying. He concluded that a steam layer forming in the sheet helps to drive liquid water into the felt during impulse drying. The increased removal of liquid water is what gives

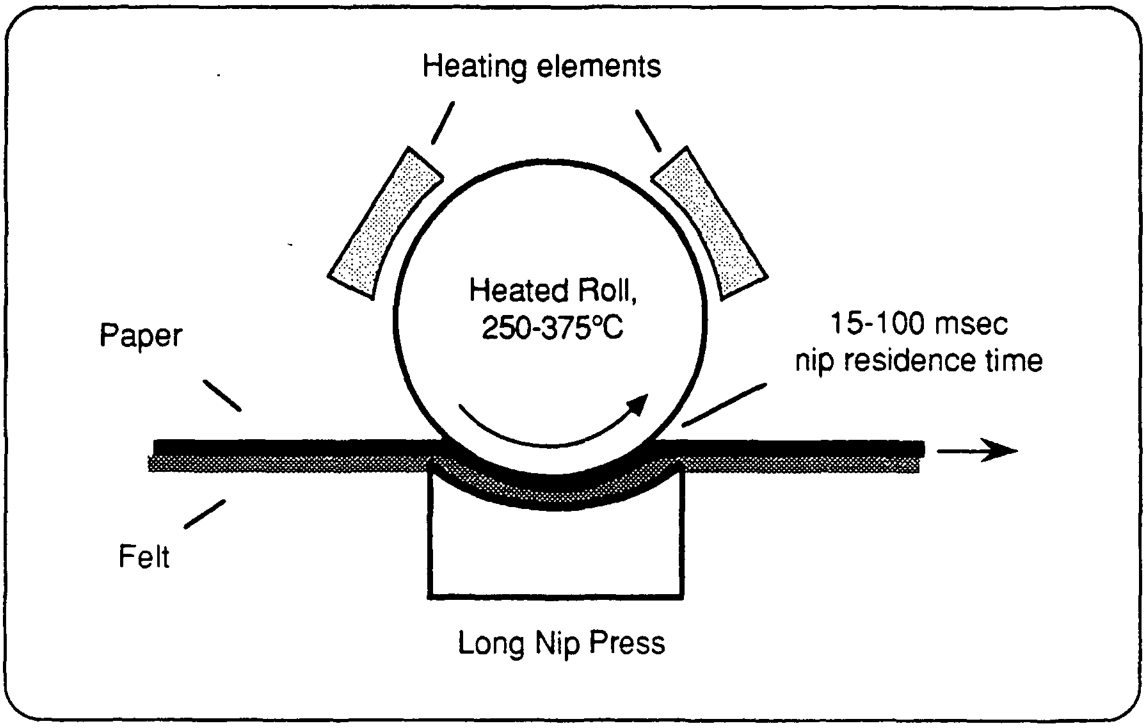


Figure 1. A possible implementation of the impulse drying concept.

impulse drying an economic advantage over pure evaporative drying. Zavaglia and Lindsay (5) applied a flash x-ray visualization technique to examine the motion of liquid tracers during an impulse drying event. In some cases, an internal steam front was detected which appeared to displace tracer away from the surface of the paper. The steam layer was not always detected, however, and the role of the steam zone in assisting water removal is not clear. Numerical modeling has also been applied to better grasp the role of displacement and unsteady-state heat transfer in impulse drying (6). Results from that work have pointed to the importance of phase-change heat transfer during the impulse drying process.

Heat transfer appears to be the key to impulse drying. It is the source of the advantages of impulse drying, and, when improperly controlled, is the cause of its main disadvantage — delamination (1,7). Surface temperature and corresponding heat flux data for a typical impulse drying event with linerboard are illustrated in Figures 2 and 3 (8). The heat flux to the moist web of paper peaks around 3 $MW/m^2$ as the temperature of the heated metal surface drops by about 25°C. Understanding and controlling the heat flux into sheet during an impulse drying event is necessary if impulse drying is to be commercialized. Unfortunately, little is known about the details of boiling or intense phase-change heat transfer in fibrous media. Researchers have examined boiling in simple porous media such as loose sand or beds of glass spheres (9,10), and much work has been done with phase-change heat transfer in heat pipes (11), which typically employ a porous structure, but direct measurement in fibrous porous media appears to be lacking. This study was initiated to provide fundamental background information about boiling heat transfer mechanisms in fibrous media.

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 and the role of the vapor phase in impulse drying.

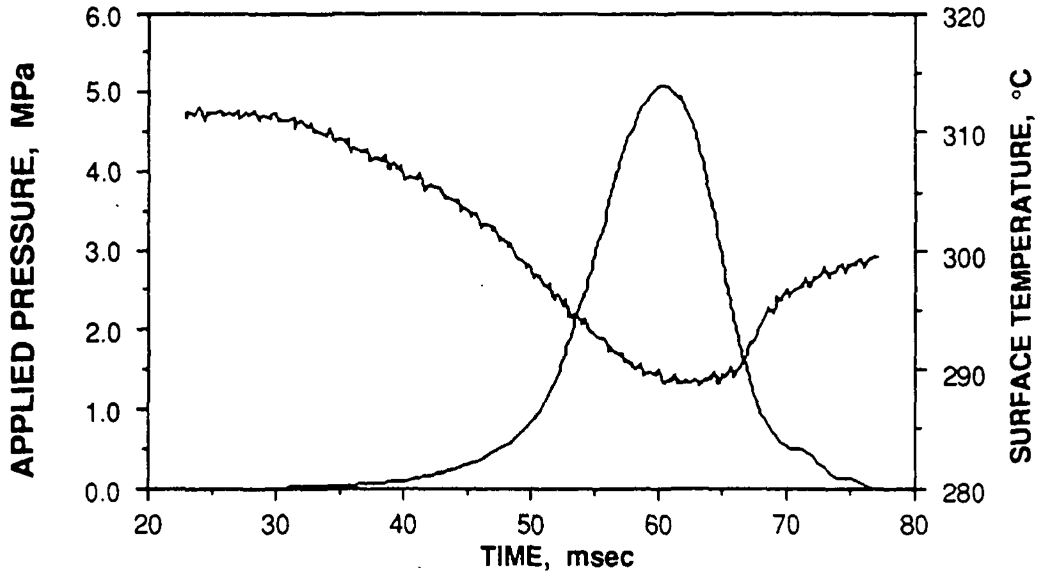


Figure 2. Platen surface temperature and applied pressure pulse during an impulse drying test with linerboard.

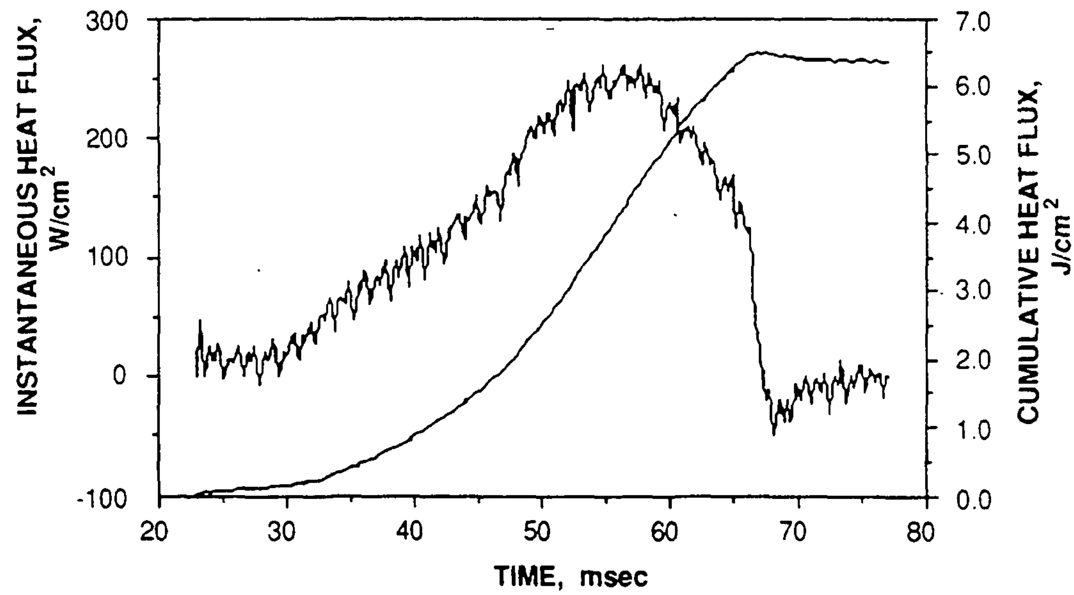


Figure 3. Heat transfer into a sheet during a typical impulse drying test (same event shown in Fig. 2).

## 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 of water in a fibrous medium (Figure 4) is discussed in detail elsewhere (12,13). Briefly, the boiling cell apparatus is composed of four systems: the boiling cell, the heat supply system, the data acquisition system, and the process control system. 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 ranges from 30 to 250 µm.

The boiling cell consists of a 9-cm ID x 110-cm long machined quartz cylinder. The fiber bed is formed in one end of the tube by filtration from a slurry having a consistency of approximately 0.1%. 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. Nine cartridge heaters are positioned symmetrically in a vertical orientation in the bottom of the heating block. Heat flow from the cartridges is metered by a silicon-controlled rectifier (SCR) based on the output signal from the surface temperature controller. Three thermocouples embedded within the block near the boiling surface measure the temperatures necessary to calculate surface temperature and heat flux. This calculation is based on the one-dimensional heat equation incorporating a curve-fitted expression for temperature-dependent thermal conductivity of the block. An analog watt transducer that measures power supply to the cartridge heaters verified the accuracy of the heat flux calculation technique.

The experimental control system developed for this apparatus provides data acquisition, heater block surface temperature control, and system pressure control. A number of type-K thermocouples and one strain-gage pressure transducer are interfaced with PID controllers and a computerized data

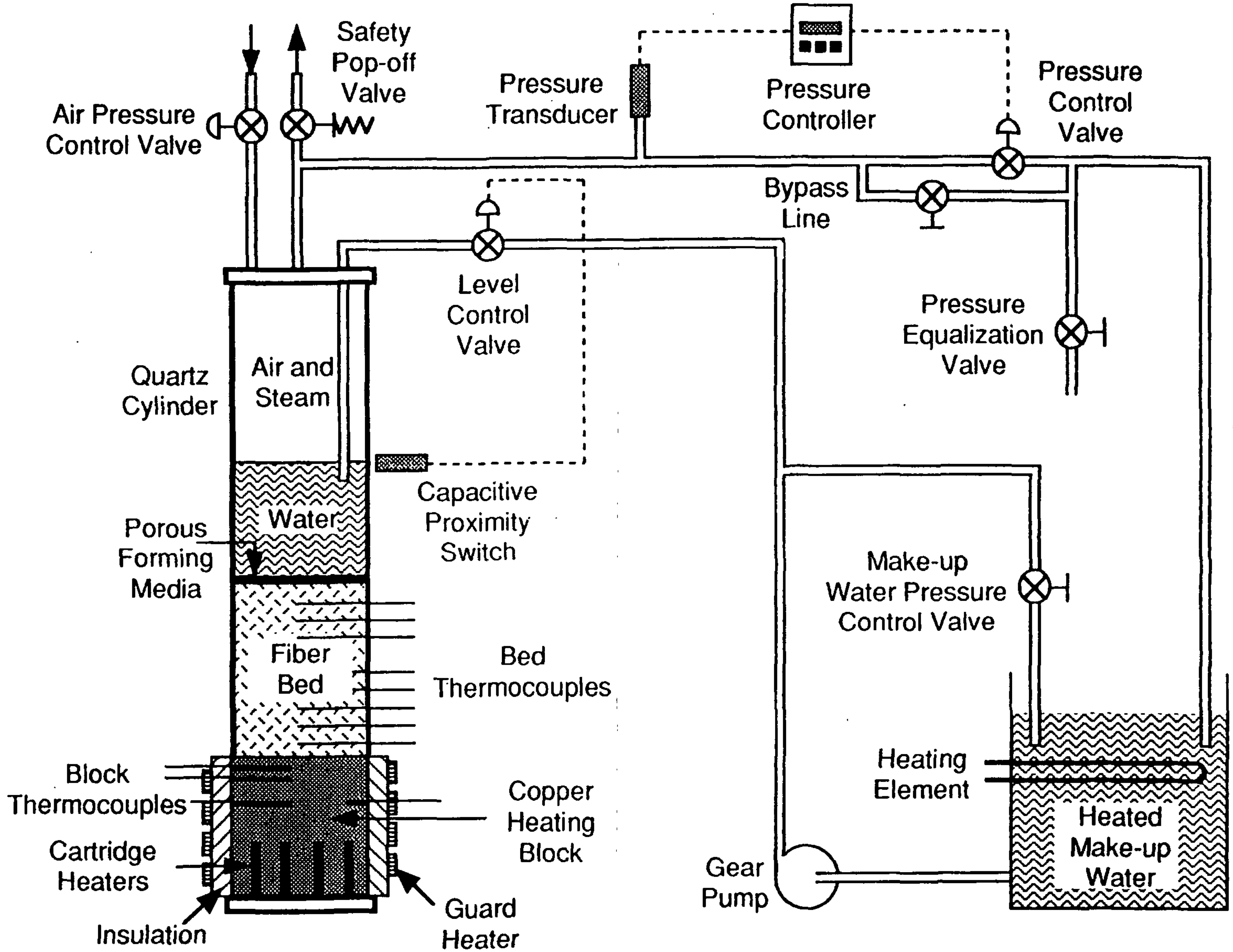


**Figure 4.** Schematic of the boiling cell apparatus.

acquisition system. Software was written to execute a steady-state boiling experiment.

## 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. In accordance with standard convention for boiling heat transfer data, log-log axes are chosen to graphically present the experimental data for this study. Based on the additive uncertainty model, the uncertainty for the calculated heat flux is 0.9 $W/cm^2$, and is 0.6°C for calculated surface temperature, both values being independent of wall superheat. 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, a catastrophic failure of the boiling cell at elevated temperatures at 0.28 MPa precluded boiling at higher pressures. The reader is cautioned that the data comparisons to be presented are only intended to illustrate trends effected by experimental parameters. Because the data to be compared are from fiber beds with similar (but not identical) average pore diameters and bed heights, the data should not be interpreted for absolute magnitudes of parametric effects. A more detailed discussion of the boiling phenomena is presented in References 14 and 15.

### Qualitative Description

Once phase-change commences, 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 due to capillary forces and gravity. This two-phase zone of counterpercolating vapor and liquid is nearly isothermal, is at the saturation temperature for the system pressure, and grows in height with heat flux. The vapor condenses at the interface with the overlying liquid-saturated zone. If the height of this zone grows to encompass the entire bed, the vapor protrudes from the top of the bed and agitates the overlying pool of liquid. Fibrous beds with heights as high as 25 cm can become fully engulfed in two-phase flow.

The nature of boiling is modified by the presence of the fibrous bed, as illustrated in Figure 5 (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

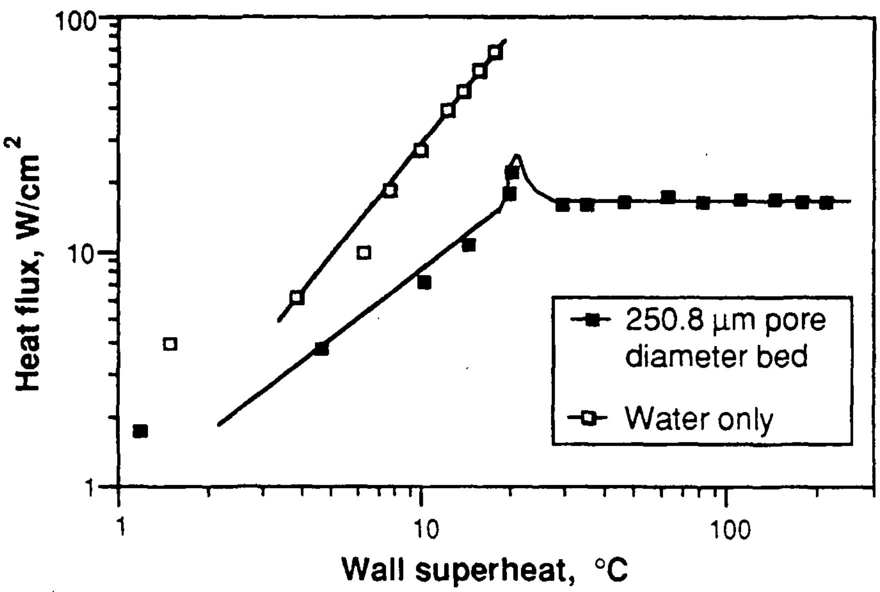


Figure 5. Typical measured boiling curves for pure water and water in a fibrous bed.

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, which is related to nucleation characteristics of the heater surface. Apparently, some form of active nucleation is occurring at voids on the heater surface, within limits posed by physical constraints of the pore structure. It is during this nucleate-type regime that the isothermal, two-phase counterpercolation zone develops. The porous medium interferes with the process of bubble growth and detachment, making nucleate boiling less effective than boiling in free liquid.

In the second regime, called the constant-heat-flux regime, the heat flux is independent of wall superheat, and is apparently controlled by the rate of liquid flow to the heater surface influenced by capillary forces in the bed. This suggests that a thin dry zone forms near the surface, through which heat travels by conduction to a two-phase zone where water is vaporized. An increase in surface temperature will cause the dry zone to grow until the conductive flux across that zone once again equals the flux required to evaporate water flowing down at a constant rate. This obviously depends on the saturation level and pore size distribution of the bed.

The point of transition between the two regimes, called the transitional heat flux (THF), can exhibit moderate instability. The beds with average pore diameters greater than 220 μm exhibit a peak heat flux that has a magnitude greater than that of the constant-heat-flux regime. At the THF, a dramatic change in the fluid flow phenomena reduces the heat-absorbing capacity of the bed. Attempts to increase surface temperature beyond the THF yield a rapid rise in surface temperature (typically, an increase of 10 to 15°C in a period of 10 to 15 seconds) that is arrested by the surface temperature control system. The observed peak heat flux and subsequent decline to the constant-heat-flux regime for beds of large average pore diameter may be related to the saturation profile.

## The Effect of Average Pore Diameter

The average pore diameter of the bed significantly influences boiling phenomena, as illustrated in Figure 6. 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. Nucleation is probably inhibited, and the resistance to vapor flow away from the heater surface increases, in proportion to

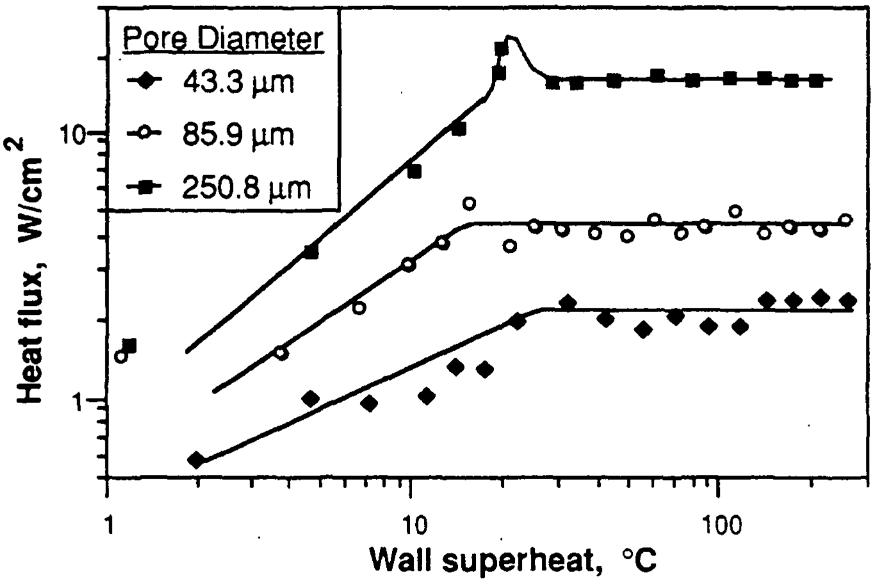


Figure 6. The effect of average pore diameter on the boiling curve at atmospheric pressure.

the diameters of the flow channels. Any accumulation of vapor at the surface will increase the resistance to heat transfer at the surface.

Behavior at the THF depends on 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 boiling regimes with an associated rapid escalation in surface temperature. However, the small average-pore-diameter beds (35 to 90 μm) exhibit a smooth transition. This difference in behavior at the THF may be related to the curvature of the saturation profile in the bed.

The magnitude of heat flux in the constant-heat-flux regime is directly related to average pore diameter. Obviously, as the pore diameters in a given type of porous medium decrease, the permeability decreases, thus lowering the rate of liquid supply to the surface and also lowering the steady-state phase-change heat flux.

### The Effect of System Pressure

Figure 7 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. The effects of a higher bed saturation due to the increased vapor phase density at elevated pressures are not apparent in the heat flux data for the nucleate-type regime of wall superheats below about 20°C. This suggests that geometric constraints dominate pressure effects in controlling nucleation. The nucleate-type regime 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 THF is exacerbated as the system pressure increases. As the boiling process approaches the THF, the relationship between wall superheat and heat flux reverses; the wall superheat actually decreases as higher heat fluxes are attained, as exhibited by the backward bend in the boiling curve. 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 transitional is reproduced in all of the pressurized boiling runs for beds with average pore diameters above about 220 μm.

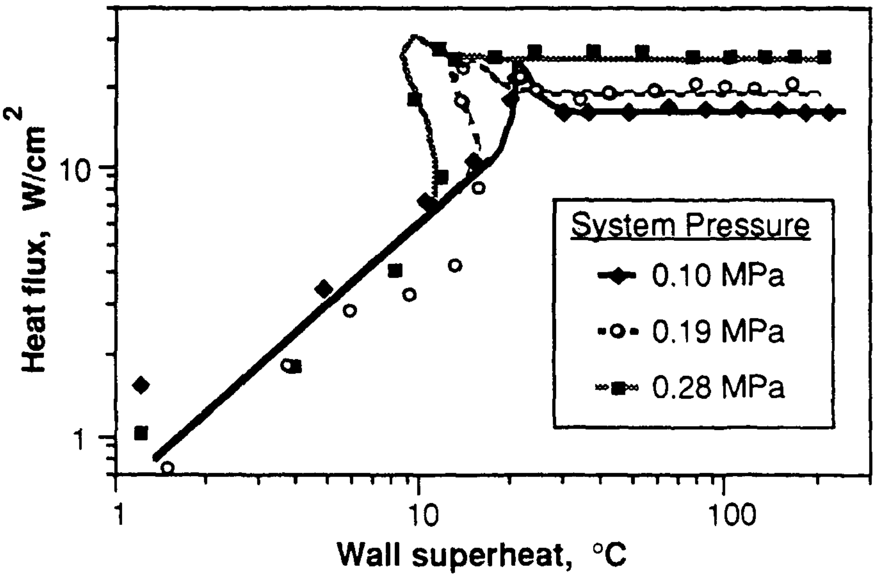


Figure 7. The effect of system pressure on the boiling curve. Average pore diameter = 250 μm.

The effect of pressure on the magnitude of heat flux in the constant-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 heat flux in the constant-heat-flux regime is greater under pressure than at atmospheric conditions.

## IMPLICATIONS FOR IMPULSE DRYING

While the fundamental nature of this study precludes direct application of the results to real impulse drying, some practical insight can be gained into the possible effect of sheet pore size and internal vapor pressure on heat transfer to the sheet. Data collected by Lavery (5) indicate some interesting phenomena as the impulse drying event is extended. As illustrated in Figure 8, 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 constant-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 (5). At this point, heat flux may 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 exhibiting counterpercolation of steam and liquid water may deliver liquid to the plane of evaporation while allowing vapor to flow away. Vapor leaving the two phase zone may condense in cooler portions of the sheet, or may form "viscous fingers" which break through the liquid zone and allow vapor to leave the sheet.

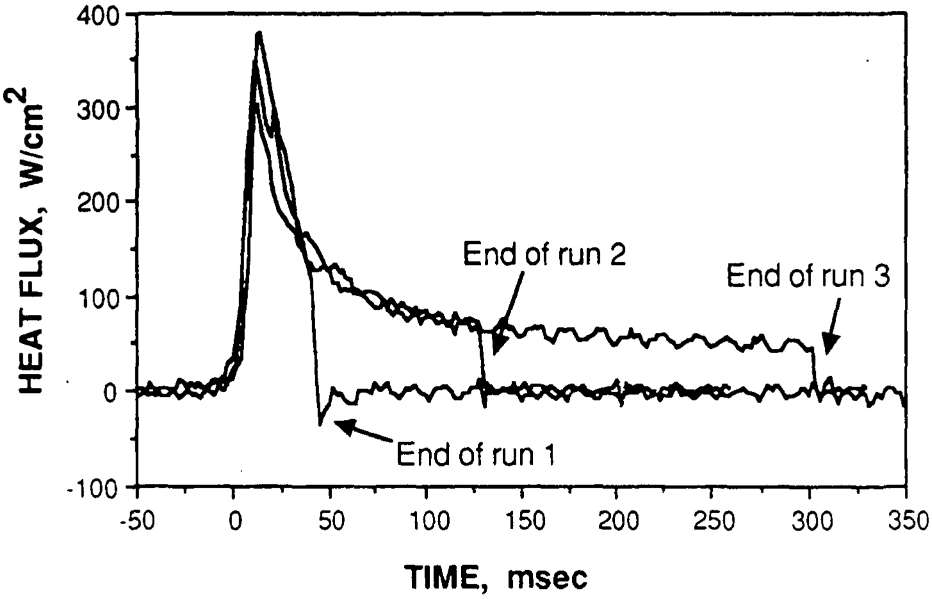


Figure 8. Heat flux measurements from multiple impulse drying tests with linerboard. Only nip residence times was varied.

Thus, the heat flux will depend to a large degree on the pore structure of the sheet in this regime. A true steady-state is not achieved, of course, and the heat flux does continue to decrease with time, as expected. (In fact, if the water in the sheet were replaced with a similar material that could not boil or flow, meaning that heat transfer would be by transient conduction only, a similar heat flux curve would be obtained. Heat flux data alone are inadequate to deduce the physics of impulse drying.)

Support for the significance of sheet structure in controlling heat flux during impulse drying exists in the correlations developed for heat flux in the boiling study. Mathematical treatment of the boiling data using dimensional analysis resulted in a unique dimensionless group that was found to be of major significance in correlating the data of both boiling regimes (9,12). The constant-heat-flux number, defined as follows,

$$CHF = \frac{\eta_l^2}{\overline{D}\,\rho_l\,\sigma}, \tag{1}$$

where $\eta_l$ = liquid viscosity,
$\overline{D}$ = average pore diameter of the fibrous medium,
$\rho_l$ = liquid density, and
$\sigma$ = surface tension,

represents the balance between capillary forces conducting liquid through the pore structure of the medium and viscous forces resisting liquid flow. The statistical significance of this group emphasizes the role of pore structure in controlling heat flux in the model boiling system. Likewise, it is expected that sheet pore structure is one factor that controls heat transfer in impulse drying.

Another insight emanating from this work is that papermaking operations that reduce the average pore diameter of the sheet may be detrimental to the quantity of water removed during impulse drying. 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 the vapor phase. Based on this research, heat flux appears to 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 increase 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 provide insight into the role that boiling heat transfer plays in impulse drying. The average pore diameter of the bed and the system pressure are two factors that display a significant impact on both regimes encountered during boiling in a model fibrous medium. Consequently, the pore structure of the fiber sheet and the internal pressure that builds during impulse drying are expected to have a major impact on heat flux and the quantity of water removed during impulse drying. 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.

## ACKNOWLEDGMENTS

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