UNIVERSITY OF CINCINNATI

DATE : Dec. 15, 2002

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hereby submit this as part of the requirements for the
degree of:

Master of Science

in:

Mechanical Engineering

It is entitled:

The Dynamic Characteristics of

a Liquid-Gas Interface in Microscale Pores

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The Dynamic Characteristics of a Liquid-Gas Interface in Microscale Pores

A thesis submitted to the

Division of Research and Advanced Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Master of Science

Department of Mechanical, Industrial and Nuclear Engineering
College of Engineering

2002

by

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B.S., Sung Kyun Kwan University, Korea, 1994

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Abstract

For both Loop Heat Pipes, being developed as a thermal control device for microelectronics in space applications, and the de-watering process in a vibro-separator, the dynamic characteristics of a liquid-gas interface inside micropores greatly affects the efficiency of the entire system.

In the pharmaceutical industries, product particles are discharged in the form of a dilute slurry from a reactor to a de-watering device, such as a vibro-separator. For extremely small pores, gravity is insufficient for removing the excess water through the micropore screen. For these cases, it has been suggested that the de-watering process can be initiated by utilizing a vacuum pressure beneath the screen and applying sinusoidal vibration to the screen.

To understand the phenomena of de-watering from the product screen of a vibro-separator utilizing vibration and pressure, a single liquid-filled micropore is studied. In past studies [8], the Navier-Stokes and Young-Laplace equations have been used to describe the dynamic motion of the liquid column and liquid-gas interface.

A major goal of this study is to experimentally verify this model. In particular, comparison is made between the amplitude and frequency of acceleration required to cause the bubble burst through predicted theoretically and measured experimentally.

The Lexan wicks having several pores with a uniform diameter of 50 μm , 100 μm , 500 μm and 1 mm are utilized. Depending upon the size of the micropores, two different types of tests were performed. One test utilized no external pressure difference across the wick and other test utilized a pressurized upper chamber.

Dedicated to my loving parents

Acknowledgements

Sincere and whole hearted expressions of gratitude are given to my academic advisor Dr. Frank M. Gerner for his wise counsel, guidance and valuable advice throughout this research. I also want to express my gratitude to all members of my thesis committee, Dr. Thurman H. Henderson and Dr. Michael Kazmierczak for providing suggestion and invaluable comments.

I would like to thank Dr. Chong H. Ahn and Xiaoshan Zhu for their help to prepare samples used in this experimental test. I would also like to thank Dr. Randall J. Allemang for supplying the experimental facilities during these tests. Thank you so much to my friends Kyesang Yoo and Dr. Hyoung Jin Cho for their ideas and support about this research. As my lab-mate, I thank Yuelel Yang about his mathematical model made this thesis stronger.

It gives me immense pleasure to dedicate this thesis to my parents and my sister. Your endless love, encouragement and confidence in me have been a constant source of inspiration throughout my life.

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Nomenclature

A	amplitude (m)
a	acceleration (m/s ²)
C	curvature of the interface
D	dimensionless parameter
g	gravity (m/s ²)
H	thickness of the wick (m)
h	height of the liquid on the wick (m)
k	stiffness
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P _c	capillary pressure
P	pressure (Pa)
r _c	pore size (m)
Re _k	kinetic Reynolds number
S	displacement of the moving coordinates (m)
T	characteristic time scale (s)
t	time
U	velocity of the moving coordinates (m/s)
u	velocity (m/s)
V	volume (m ³)

Greek symbols

β	contact angle
ρ	mass density (kg/m ³)
σ	surface tension (N/m)
η_0	maximum depth of the meniscus cap (m)
μ	viscosity
ν	kinetic viscosity (m ² /s)
ω	frequency (s ⁻¹)
ω_o	applied frequency (s ⁻¹)
ω_n	natural frequency (s ⁻¹)
ΔP	pressure difference (Pa)

Superscripts

*	dimensionless variable
---	------------------------

Subscripts

z	z-direction component
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1. Introduction

The dynamic characteristics of a liquid-gas interface inside a micropore help determine the behavior of the wick in a micro porous Loop Heat Pipe (being developed as a thermal control device for space applications) and the de-watering process which occurs within a vibro-separator in chemical, medical, and pharmaceutical industries.

1.1 LHP and de-watering process

The following briefly explains the LHP and de-watering processes, and discusses why the dynamic characteristics are important.

1.1.1 Loop Heat Pipe

The Loop Heat Pipe (LHP) was first invented in the former Soviet Union in the early 1980's and is being developed as a thermal control device for space applications. It is a two-phase thermal device for cooling microelectronics and solar concentrators and utilizes the evaporation and condensation of a working fluid to transfer heat.

The operating principle of the LHP is as follows. As heat is applied to the evaporator, liquid is vaporized and evaporator chamber's pressure is increased. Meniscus formed at the liquid/vapor interface in the evaporator wick is supported by capillary forces even though pressure force pushes it down. Vapor flows through the vapor line to the condenser and condenses in there. Liquid is back to the evaporator due to pressure difference. The waste heat from the heat source provides the driving force for the circulation of the working fluid and no external pumping power is required. [2]

There are several ways to circulate the fluid in the system. In this thesis, the method which utilizes a Coherent Porous Silicon (CPS) wick being developed at the University of Cincinnati is introduced. This CPS wick, which is still being developed, is located inside the evaporator and has thousands of pores, which are $2 \sim 20 \mu\text{m}$ in diameter, contained over an area of one square centimeter. [3]

The CPS wick which has high pumping capability to suck the working fluid into the evaporating chamber plays an important role in fluid circulation. If burst through of the meniscus occurs inside the wick, it is a very serious problem due to the sudden failure of the device. So it is necessary to fully understand the dynamic characteristic of a liquid-gas interface inside the pore of the CPS wick, since it is an essential part in the whole system.

1.1.2 De-watering Process

In the pharmaceutical, chemical, food, medical, and environmental industries, product particles are usually discharged from the product reactors in the form of dilute slurries. Before drying, it is necessary to remove the excess water from the dilute slurry.

In some applications, a vibro-separator is used for de-watering and drying. After the wet product cake is inserted upon the product screen the excess water is removed through the fine holes in the product screen. [4]

For the case of very small pores (less than approximately $10 \mu\text{m}$), the capillary forces are so strong that the excess water will not flow through the pores. Consequently, the drying process requires a great deal of time. One possible method is to apply a

vacuum pressure to the lower side of the wick. Another way to initiate de-watering, and decrease the drying time, is by vibrating the product plate.

By understanding the relationship between the diameters, thickness of the product screen and vibration parameters, such as frequency and amplitude, the de-watering process can be greatly improved.

1.2 The Goals of this Thesis

A clear understanding of the dynamic characteristics of the liquid-gas interface inside a micropore is essential for improving the design of the system.

Another goal of this study is to compare the experimental data and the mathematical model, validate the model and, if necessary, modify the mathematical model.

A test facility and jig similarly designed to an actual vibro-separator, is used to study the effects of pore diameter, thickness of the wick, relationship between the frequency and the amplitude of the acceleration, and relationship between the pressure and the amplitude of the acceleration.

2. Mathematical Modeling

As mentioned previously, before de-watering can be initiated, it is necessary for the forces on the top or liquid side of the interface to exceed the sum of the capillary forces and forces on the bottom or gas side of the interface. When they do, the liquid ruptures the interface. This phenomenon is referred to in this manuscript as Bubble Burst Through (BBT).

In order to mathematically model the dynamic interface, it is necessary to make certain assumptions. The pores are all of uniform diameter and spacing (see Fig. 2.1). It is also assumed that a thin liquid film exists upon the top surface of the wick. Since this liquid layer and the wick are both thin, the hydrostatic forces can be neglected.

In this chapter, the dynamic characteristics of a liquid column in the wick are studied by simulating a sinusoidal vibration of the wick and pressure difference across the wick to enhance the de-watering process.

2.1 Dynamic Modeling

A dynamic model has been developed by Yuelel Yang a graduate student working in the same research group at the University of Cincinnati. The liquid accumulated on the top of the product screen inside the pores and the liquid-gas interfaces are shown in Fig. 2.1. If the pore diameters are extremely small, due to capillary forces, the liquid is not able to pour down under its own gravity.

Due to a pressure difference across the wick and applied vibration, a liquid-gas interface occurs on the bottom of the liquid column with the shape of a meniscus.

Figure 2.1 The meniscus in porous wick.

To simplify the problem, only one liquid column in the pore of the wick is considered.

Figure 2.2 Coordinates of the model

In an earlier work, Yang [10] demonstrated that it is permissible to model a single pore to predict BBT if the ratio between the center to center spacing (L) and pore diameter (d) exceeds 10 ($L/d \gg 10$). If the center to center pore spacing is less than this value, the asymptotic absorbed film region for adjacent pores intersects.

Coordinates (R, Z) are the absolute coordinates and coordinates (r, z) are the relative ones, which are fixed on the porous wick. Coordinates (η , γ) are moving with the center of the meniscus.

Several assumptions were used in the model.

1. The fluid is incompressible.
2. The fluid flow is fully developed because the height of the wick is much larger than the radius ($H \gg r_c$).
3. The pores are circular.
4. Disjoining and conjoining pressures are not considered.

Yang was able to calculate, at least for static Burst Through, that these forces may be neglected for pore diameter exceeding 1 μm .

5. No-slip condition at the wall.
6. The material is fully wetted.

For the static case, the capillary pressure is:

$$P_c = \frac{2\sigma \cos \beta}{r_c} \quad (1)$$

By using the conventional Young-Laplace equations, the meniscus profile can be obtained:

$$\Delta P = \sigma C = \sigma \left[\frac{\frac{\partial^2 \eta}{\partial \gamma^2}}{\left[1 + \left(\frac{\partial \eta}{\partial \gamma} \right)^2 \right]^{\frac{3}{2}}} + \frac{1}{\gamma \left[1 + \left(\frac{\partial \eta}{\partial \gamma} \right)^2 \right]^{\frac{1}{2}}} \right] \quad (2)$$

The Navier-Stokes equation in cylindrical coordinates (r, θ , z) can be written:

$$\rho \frac{dU}{dt} = \mu \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_z}{\partial \theta^2} + \frac{\partial^2 u_z}{\partial z^2} \right] - \frac{\partial P}{\partial z} + \rho g_z \quad (3)$$

If S is the displacement of the (r, z) coordinate relative (R, Z), the absolute acceleration of the particle are related to its velocity V relative to moving system:

$$a = \frac{dU}{dt} = \frac{d^2 s}{dt^2} + \frac{dV}{dt} \quad (4)$$

Since the pore length, H, is much larger than the pore radius, r_c , the fluid flow is fully developed and the effect of gravity can be neglected. It is assumed that flow is one dimensional. Therefore the acceleration in the θ and z directions also neglected. From Equations (3) and (4), a more simple equation is obtained:

$$\frac{d^2 s}{dt^2} + \frac{dV}{dt} = \nu \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_z}{\partial r} \right) - \frac{1}{\rho} \frac{\Delta P}{H} \quad (5)$$

If the system is vibrated with an amplitude A and frequency ω_o , then the displacement of the system (r, z) relative to (R, Z) will be:

$$S = A \cos \omega_o t \quad (6)$$

Substituting Equations (5) and (6) into Equation (4)

$$\frac{\partial u_z}{\partial t} = \nu \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_z}{\partial r} \right) - \frac{1}{\rho} \frac{\Delta P}{H} + A \omega_o^2 \cos \omega_o t \quad (7)$$

One obtains the mass flow rate at a give time:

$$m = \rho \int_0^{r_c} u_z(r) 2\pi r dr = -\rho \frac{D}{Dt} \left\{ \int_0^{r_c} [\eta_0 - \eta(\gamma)] 2\pi \gamma d\gamma \right\} \quad (8)$$

For the numerical analysis, the dimensionless forms of the equations are needed.

The following non-dimensional was used:

$$u_z^* = u_z / (r_c / T)$$

$$r^* = r / r_c$$

$$t^* = t / T$$

$$\Delta P^* = \Delta P / (\sigma / r_c)$$

$$m^* = m / (\rho r_c^3 / T)$$

$$\eta^* = \eta / r_c$$

$$\gamma^* = \gamma / r_c$$

A characteristic time scale is:

$$T = r_c \sqrt{\frac{\rho H}{\sigma}} \sim \frac{1}{\omega_n} \quad (9)$$

The following dimensionless equations are acquired.

$$\Delta P^* = \left[\frac{\frac{\partial^2 \eta^*}{\partial \gamma^{*2}}}{\left[1 + \left(\frac{\partial \eta^*}{\partial \gamma^*} \right)^{3/2} \right]} + \frac{1}{\gamma^* \left[1 + \left(\frac{\partial \eta^*}{\partial \gamma^*} \right)^2 \right]^{1/2}} \right] \quad (10)$$

$$\frac{\partial u_z^*}{\partial t^*} = - \left[\Delta P^* - \frac{AT^2 \omega_o^2}{r_c} \cos(\omega_o T t^*) \right] + \frac{\nu T}{r_c^2} \left[\frac{1}{r^*} \frac{\partial}{\partial r^*} \left(r^* \frac{\partial u_z^*}{\partial r^*} \right) \right] \quad (11)$$

$$m^* = \int_0^1 u_z^*(r^*) 2\pi r^* dr^* = - \frac{D}{Dt} \left\{ \int_0^1 [\eta_0 / r_c - \eta^*(\gamma^*)] 2\pi \gamma^* d\gamma^* \right\} \quad (12)$$

For the fluid inside the liquid column, the no-slip boundary condition is valid and it is assumed that the fluid is initially static. The boundary and initial conditions governing the fluid inside the pores are:

$$u_z^*(1, t^*) = 0$$

$$\frac{\partial u_z^*}{\partial r^*}(0, t^*) = 0$$

$$u_z^*(r^*, 0) = 0$$

Also, there are boundary and initial conditions governing the meniscus shape:

$$\eta^*(0) = 0$$

$$\frac{\partial \eta^*}{\partial \gamma^*}(0) = 0$$

With Equations (10), (11), (12) and boundary and initial conditions, the velocity profiles inside the liquid column and the transient meniscus profiles are acquired by using a finite difference method.

2.2 Natural frequency

What is the natural frequency? If a system, after an initial disturbance, is left to vibrate on its own, the frequency with which it oscillates without external forces is known as its natural frequency. [6]

Now, consider the movement of the fluid inside the porous wick. It is similar to a classical damped spring-mass system. When the fluid inside the pore is oscillated up and down, by either applying vibration or a sudden pressure difference across the wick, the liquid column which is trapped in the pore also has a natural frequency. Assuming the liquid column inside the pore is a classical spring-mass system like in Fig. 2.3.

Figure 2.3 Damped spring-mass system

Its natural frequency is:

$$\omega_n = \sqrt{\frac{k}{m}} \quad (13)$$

In this system, the restoring force due to the surface energy or changing of the meniscus shape at the bottom of liquid column is:

$$k = \frac{df}{dz} \approx \frac{\Delta f}{\Delta z} \quad (14)$$

The volume of the meniscus cap is dependent on the angle.

$$V(\theta) = \frac{\pi r_c^3}{3} \frac{\cos \theta (2 + \sin \theta)}{(1 + \sin \theta)^2} \quad (15)$$

The change of contact angle is $\Delta\theta$. If we consider it is linear, the change of the volume is:

$$\Delta V = \frac{\partial V}{\partial \theta} \Delta \theta = -\pi r_c^3 \frac{1}{(1 + \sin \theta)^2} \Delta \theta \quad (16)$$

The change of the volume in the whole liquid column is equal to the change of the meniscus cap's volume due to the condition of geometry, $h \ll r_c \ll H$. So one can approximate the average displacement of the liquid column:

$$\Delta z = \frac{\Delta V}{\pi r_c^2} \quad (17)$$

The force in the z direction due to the surface tension is:

$$f \approx 2\pi r \sigma \cos \theta \quad (18)$$

From the Equations (14), (17), and (18)

$$k = \frac{\Delta f}{\Delta z} = \frac{2\pi r_c \sigma [\cos(\theta + \Delta\theta) - \cos \theta]}{\Delta V / (\pi r_c^2)} \quad (19)$$

Assuming, $\Delta\theta$ is small

$$\cos \Delta\theta \approx 1, \text{ and } \sin \Delta\theta \approx \Delta\theta$$

Then,

$$k = \frac{2\pi\sigma r_c \sin \theta \Delta \theta}{r_c \Delta \theta / (1 + \sin \theta)^2} = 2\pi\sigma \sin \theta (1 + \sin \theta)^2 \quad (20)$$

Substituting Equation (13) into Equation (20), and calculates the mass in the pore as

$$m = \rho H r_c^2$$

The natural frequency is:

$$\omega_n \sim 2\pi \sqrt{\sin \theta (1 + \sin \theta)^2} \sqrt{\frac{\sigma}{\rho H r_c^2}} \quad (21)$$

This natural frequency is essentially the same as that used for an inverse time scale in Equation (9), which was obtained from scaling Equation (7):

$$\omega_n \sim \sqrt{\frac{\sigma}{\rho H r_c^2}} \quad (22)$$

2.3 Bubble Burst Through (BBT) Curve.

The meniscus of the liquid column inside a pore oscillates due to the movement of the wick or a pressure difference. The liquid-gas interface will burst when the transient pressure difference across the interface is larger than the maximum capillary pressure.

There are three ways to precipitate Burst Through. One is applying a pressure difference across the wick. Another is vibrating a wick with a proper frequency and amplitude. The other is applying a pressure and vibration simultaneously.

A dimensionless parameter, the kinetic Reynolds number, which is the ratio between the inertial force and viscous force results from a scaling of Equation (11) and is important for predicting Bubble Burst Through.

$$\text{Re}_k = \frac{r_c^2}{\nu T} = \frac{r_c}{\nu} \sqrt{\frac{\sigma}{\rho H}} \quad (22)$$

If the wick pore's diameter, thickness, and applied frequency are given, we can predict the Burst Through point in the CPS wick or porous metal screen by using a numerical simulation presented in 2.1.

Figure 2.4 BBT Curve using a mathematical modeling

As an example, for a wick with a diameter of 1 mm and thickness of 12 mm, the kinetic Reynolds number is 38.5. If there is no applied pressure difference across the wick, BBT curve is shown in Fig. 2.4.

3. Measurement

In order to verify the Mathematic Model presented in Chap. 2, a series of experiments were performed. Lexan wicks, each having several pores were dynamically tested. Information concerning the wick samples, setup of the experimental facilities, test procedure, and definition of the bubble burst through in an actual test are discussed in this chapter.

3.1 Wick Samples

To test the dynamic characteristics of the liquid column inside pores, several types of Lexan wicks were prepared in order to investigate the effect of diameter, thickness and aspect ratio of the thickness to diameter. Seven wick samples were prepared.

Figure 3.1 Wick samples

The various diameters, thicknesses, materials, number of pores, and aspect ratio are shown in Table 3.1.

Diameter (d)	1 mm	1 mm	1 mm	500 μ m	500 μ m	100 μ m	50 μ m
Thickness (t)	1 mm	6 mm	12 mm	1 mm	6 mm	1 mm	1 mm
Ratio	1	6	12	2	12	10	20
Materials	Lexan	Lexan	Lexan	Lexan	Lexan	Lexan	Lexan
Number of holes	2	2	2	3	1	5	2

Table 3.1 Wick sample

3.2 Experimental Setup

Two different types of tests were performed. For one, vibration was applied with no external pressure difference across the wick. The second, pressurized the upper side of the wick, before vibrating the wick.

3.2.1 Vibration test with no external pressure difference

For no pressure difference across the wick, the jig shown in Figs. 3.2, 3.3, and 3.4 was used. Fig. 3.3 is the upper side view of the jig and Fig. 3.4 is the lower side view.

Figure 3.2 Jig for a vibration test with no external pressure difference

Figure 3.3 Jig for a vibration test with no external pressure difference (upper view)

Figure 3.4 Jig for a vibration test with no external pressure difference (lower view)

The wick is fixed between the upper and bottom plate with screws and nuts. A gasket between the upper plate and wick prevent leakage of the liquid.

There is a circular hole for liquid injection and insuring that there is no external pressure difference across the wick (Fig. 3.3). There is a space below the wick for checking the condition of the liquid's meniscus and the initiation of burst through (Fig. 3.4). The bottom plate has 8 holes. Four holes are used to fix the wick inside the jig. The others are used to connect the dynamic shaker and jig (Fig. 3.5). The liquid is injected into the upper side of the wick through the circular hole about 0.15 ml per test (Fig. 3.3).

Figure 3.5 Connection with the jig and the dynamic shaker's moving plate

After fixing the jig on the dynamic shaker, the dynamic signal analyzer (HP analyzer) is set. After choosing the desired frequency and pushing the start button, the dynamic signal analyzer sends a pure sinusoidal signal to the amplifier. As the amplitude

slowly increases, the dynamic shaker's top plate oscillates with the desired frequency and amplitude (Fig. 3.8).

Using the acceleration sensor, which is adhered to the jig, the actual frequency and amplitude are determined using the analyzer's results display screen. For the example shown in Fig. 3.6, the screen shows that the amplitude and frequency of the acceleration are 47.81 mV and 100 Hz at this time. From the sensitivity value of acceleration (10.583 mV/g), the real amplitude can be calculated (4.518 g). While slowly increasing the amplitude of the vibration, the change of meniscus shape is observed and finally the burst through point of the meniscus can be acquired.

Figure 3.6 Analyzer screen to show the frequency and amplitude of acceleration

Fig. 3.7 is a schematic diagram of the vibration test with no external pressure difference and Fig. 3.8 is a picture of the actual and test equipment.

Figure 3.7 Schematic diagram of the vibration test with no external pressure difference

Figure 3.8 Laboratory equipment for vibration test with no external pressure difference

Detailed information concerning the laboratory equipment is shown in Table 3.2.

Dynamic Signal Analyzer	HP 35660A, 2 Channel
Amplifier	MB Dynamics (Model SS250)
Power Supply	PCB(I.C.P. type) Model 482A
Dynamic Shaker	MB Dynamics
Accelerometer	PCB 303A03, SN-15225(Sensitivity:10.3007 mV/G)
Cable	2 EA

Table 3.2 Laboratory equipment list for vibration test with no external pressure difference

3.2.2 Vibration test at the pressurized condition

For pore diameters of less than 500 μm , it is difficult to obtain the burst through solely utilizing vibration. For these cases, the upper side of the wick is pressurized while the wick is vibrated. Burst through is then obtained at lower vibration levels.

Figure 3.9 Jig for a pressurized condition.

The jig shown in Fig 3.9, 3.10 and 3.11 is used for this pressurized test

Figure 3.10 Jig for a pressurized condition (upper view)

Figure 3.11 Jig for a pressurized condition (lower view)

There are three plates for this jig; upper, bottom and cap. It is similar to the jig shown in Fig 3.2 except the cap has an inlet tube for applying pressure.

After fixing the wick between the upper and bottom plate using the screws, nuts and bolts, the liquid is injected through the inlet tube (Fig. 3.10). When the liquid is injected, a syringe is used to inject an exact quantity of liquid volume of approximately 0.25 ml.

The stainless steel inlet tube is connected with the flexible tube after the jig is attached to the dynamic shaker (Fig. 3.13).

A syringe connected with a jig is utilized to pressurize the upper chamber. A pressure sensor detects the pressure on the upper side of the wick. A multi-meter receives the signal from the sensor and displays a digital number about the pressure on the upper side of the wick (Fig. 3.13).

Figure 3.12 Schematic diagram of the vibration test at the pressurized condition

Figure 3.13 Laboratory equipment for vibration test at a pressurized condition

The remaining procedures are the same as the vibration test with no external pressure difference. The pressurized tests are shown in Figs. 3.12 and 3.13.

Detailed information concerning the laboratory equipment is shown in Table 3.3.

Dynamic Signal Analyzer	HP 35660A, 2 Channel
Amplifier	MB Dynamics (Model SS250)
Power Supply 1	PCB(I.C.P. type) Model 482A
Power Supply 2	Health 2718 tri power supply
Dynamic Shaker	MB Dynamics
Accelerometer	PCB 303A03, SN-15225 (Sensitivity:10.3007 mV/G)
Multi-meter	9202 Digital Multimeter
Pressure Sensor	Pressure Transducer PX26-001GV
Cable	2 EA

Table 3.3 Laboratory equipment for vibration test with a pressurized upper chamber

3.3 Test Procedure

The following describes the exact experimental procedure used in these tests.

3.3.1 Vibration test at the atmospheric pressure condition

- (1) Turn on the power for all the equipment.
- (2) Fix the wick inside a jig utilizing screws and bolts.
- (3) Inject the liquid (water) on the upper side of the wick.
- (4) Attach the jig to the dynamic shaker using screws (Fig. 3.5).
- (5) Initialize the signal generator (HP analyzer).
- (6) Press the source button to send a signal to the dynamic shaker and initiate vibration.
- (7) Slowly increase the amplitude of the dynamic shaker by using an Amplifier. Then, observe the meniscus at the bottom side of the wick.
- (8) Slowly increase the amplitude of the acceleration until burst through occurs.
- (9) Read the amplitude level from the screen of the HP analyzer (Fig. 3.6).
- (10) Turn off the signal.
- (11) Turn off the power of the laboratory equipment.

3.3.2 Vibration test at the pressurized condition

- (1) Turn on the power for all the equipment.
- (2) Fix the wick inside a jig utilizing screws and bolts.
- (3) Inject the liquid (water) on the upper chamber of the wick using a syringe.
- (4) Connect the inlet tube in the jig with the flexible tube for pressurizing the upper chamber.

- (5) Attach the jig to the dynamic shaker using screws (Fig. 3.5).
- (6) Slowly apply the proper pressure with a syringe and check the pressure level with the multi-meter.
- (7) Initialize the signal generator (HP analyzer).
- (8) Press the source button to send a signal to the dynamic shaker and initiate vibration.
- (9) Slowly increase the amplitude of the dynamic shaker by using an Amplifier. Then, observe the meniscus at the bottom side of the wick.
- (10) Slowly increase the amplitude of the acceleration until burst through occurs.
- (11) Read the amplitude level from the screen of the HP analyzer (Fig. 3.6).
- (12) Turn off the signal.
- (13) Turn off the power of the laboratory equipment.

4. Results and Discussion

The experimental facility described in Chap. 3, is used to determine the relationship between the external forcing frequency and the amplitude of the acceleration at BBT. These experimental values are compared with the mathematical model from Chap. 2. In these tests, water is the working fluid.

4.1 Nominal and measured diameter of the wick

A manual drill is used to prepare the wicks with pore diameters of 500 μm and 1 mm. For 50 μm and 100 μm diameter holes, a laser drilling machine is utilized.

Due to errors in the manufacturing process, the measured diameter of the wick is different from the nominal diameters. The results of measurement with an electron microscope and digital caliper are shown in Table 4.1.

Nominal diameter	1 mm	500 μm	100 μm	50 μm
Measured diameter	1.16 mm	590 μm	123 μm	53.5 μm

Table 4.1 Nominal and measured diameter of the wick

In case of 50 μm (nominal diameter), there are two holes and their actual shapes are close to a square. The side length of the bigger pore is 69.3 μm and 43.6 μm . Therefore the hydraulic diameter is calculated as 53.5 μm .

The shape of the holes with nominal diameter of 100 μm , 500 μm , and 1 mm are roughly circular. Wicks whose nominal diameters are 100 μm have 5 holes (Table 3.1) and the size of each hole is 109 μm , 117 μm , 123 μm , 108.8 μm and 99.4 μm . The longest diameter, which is 123 μm , is used due to the consideration that burst through should

occur in largest diameter. In this thesis, nominal diameters are used to indicate the wick's diameter, while measured diameters are used for calculations.

4.2 Static tests

Before proceeding with dynamic tests, the capillary pressure of the wick, in a static condition, is determined. Without applying vibration, a syringe, pressure sensor, power supply, and multi-meter are utilized (Fig. 3.12). In this test, water is used as a working fluid.

Theoretical pressure values are calculated by Equation (2-1). In these calculations, surface tension (σ) is 0.072 N/m and contact angle (β) is zero. The comparison between the theoretical and measured capillary pressure are shown in Table 4.2. Actual contact angle (β) is also calculated by using measured pressure data.

Diameter (d) / Thickness (t)	Theoretical Pressure (psi)	Measured Pressure (psi)	Contact angle (β)	After reaction (psi)	Contact angle (β)
1 mm / 12 mm	0.0418	-		-	
500 μm / 6 mm	0.0708	0.0539	59.08	0.006	80.29
100 μm / 1 mm	0.3396	0.1497	63.84	0.0719	77.78
50 μm / 1 mm	0.7807	0.4012	40.42	0.1317	85.14

Table 4.2 Capillary pressure and contact angle

Measured capillary pressures are lower than the theoretical ones. Capillary pressure for a 1 mm diameter wick is difficult to measure because it is so small. The experimental result of the wick whose diameter is 500 μm agree with the theoretical result if its contact angle is 59.08 ° (100 μm is 63.84 ° and 50 μm is 40.42 ° (Table 4.2)).

For the case of small diameters, 50 μm and 100 μm , it is not possible to initiate BBT with the shaker used unless the upper chamber of the wick is pressurized. Another

way to obtain BBT is to use a working fluid which has a lower surface tension than water. Octane, ethanol, and methanol were all attempted. But there were, however, several problems during these works. One is difficulty to check the BBT point due to the characteristics of the volatilization and another is to damage the Lexan jig by chemical reactions. Like this reason, test was tried again with water, but there are quite big differences between two measured data (Table 4.2).

Due to the changing of the characteristics of the wick column's wall, capillary pressures are decreased like Table 4.2. In case of the wick whose diameter is 100 μm and thickness is 1 mm, capillary pressure is reduced 0.1497 to 0.0719 psi. These kinds of phenomena are considered that those liquid's molecules like an octane, ethanol, and methanol are attached on the wall inside the wick column's wall. Due to this contamination, a contact angle of the wick whose diameter is 500 μm is calculated like 80.29 $^{\circ}$ (100 μm is 77.78 $^{\circ}$ and 50 μm is 85.14 $^{\circ}$ (Table 4.2)).

4.3 Dynamic tests

As shown in Fig. 3.7 and Fig 3.12, two types of dynamic tests were performed depending upon the diameter as shown in Table 4.3.

Diameter (d)	1 mm	1 mm	500 μm	500 μm	100 μm	50 μm
Thickness (t)	1 mm	12 mm	1 mm	6 mm	1 mm	1 mm
No pressure difference	○	○	○	○		
Pressurized condition					○	○

Table 4.3 Dynamic test table

The wicks whose pore diameters are 500 μm or larger are dynamically tested with no external pressure difference across the wick. Wicks with pore diameters of 100 μm or

less are tested with a pressurized condition (Table 4.3). It was not possible to initiate BBT in the 50 μm and 100 μm diameter pores unless an external pressure difference was applied.

4.3.1 Dynamic test ($d = 1\text{ mm}$, $t = 1\text{ mm}$)

The first wick discussed has a pore diameter of 1 mm and thickness of 1 mm. The frequencies applied were 50, 75, 100, 125, 150, 175, and 200 Hz.

Table 4.4 shows that the amplitude of the acceleration at BBT for each frequency. This data is displayed graphically in Fig. 4.1.

Frequency	50 Hz	75 Hz	100 Hz	125 Hz	150 Hz	175 Hz	200 Hz
Acceleration	5.566	4.63	6.233	7.291	7.544	13.111	20.242
	6.407	4.063	5.714	7.556	7.117	12.959	20.91
	6.747	5.034	5.874	7.907	8.702	14.957	21.539
	6.101	4.08	6.444	7.929	8.667	14.24	20.542
	6.105	4.075	6.289	7.503	8.687	15.092	15.737
			5.183	8.287	9.609		
			4.902	8.051	9.858		
			5.065		9.11		
			6.33				
Average	6.185	4.376	5.782	7.789	8.662	14.234	19.744

Table 4.4 BBT point ($d = 1\text{ mm}$, $t = 1\text{ mm}$)

The amplitude of acceleration vs. frequency curve (minimum acceleration required to obtain BBT) is like a quadratic function and has a minimum value at 75 Hz. With a relatively small acceleration, it is possible to obtain BBT at this point. The amplitude of acceleration required to cause BBT is proportional to frequency for frequencies larger than 75 Hz. Higher amplitude of acceleration is needed to obtain BBT for frequencies

less than 75 Hz, although it was not possible to obtain experimental data for this region due to limitations of the shaker (Fig. 4.1).

Figure 4.1 BBT curve between frequency and acceleration ($d = 1 \text{ mm}$, $t = 1 \text{ mm}$)

From Equations 3-9 and 3-22, the natural frequency (ω_n) is 536.77 rad/s ($f_n = 85.43 \text{ Hz}$) and the kinetic Reynolds number is 134.19. Here, the natural frequency is a scaling value and not precise one (For these calculations, the following were used: dynamic viscosity (ν) is $10^{-6} \text{ m}^2/\text{s}$, surface tension (σ) is 072 N/m, and density of water (ρ) is 1000 kg/m^3).

Table 4.5 and Fig. 4.2 compare the experimental data with the mathematical model presented in Chapter 3.

f (Hz)	50	75	100	125	150	175	200
a (g)	6.185	4.376	5.782	7.789	8.662	14.234	19.744
ω_o/ω_n	0.585	0.878	1.171	1.463	1.756	2.048	2.341
Test	A/r_c	1.230	0.387	0.287	0.248	0.191	0.231
Numerical		4.515	1.983	0.932	0.461	0.229	0.107

Table 4.5 Comparison with Dynamic test and Numerical Method ($d = 1 \text{ mm}$, $t = 1 \text{ mm}$)

In the region where the ratio between the natural frequency and applied frequency is over 1.7, test and numerical values are similar, but less than 1.7, numerical values are higher than test (Fig. 4.2). Like Fig. 2.4 shown in chapter 2 as an example, it is minimum point near point 2.

Figure 4.2 BBT curve between Dynamic test and Numerical Method ($d = 1 \text{ mm}$, $t = 1 \text{ mm}$)

4.3.2 Dynamic test (d = 1 mm, t = 12 mm)

In this test, a wick whose diameter is 1 mm and thickness is 12 mm is used. Applied frequency in the system is 25, 50, 75, 100, 125, 150, and 175 Hz.

Table 4.6 shows that the amplitude level of the acceleration at the burst through in each frequency when diameter of wick is 1 mm and thickness is 12 mm. This data is displayed graphically in Fig. 4.3.

Frequency	25 Hz	50 Hz	75 Hz	100 Hz	125 Hz	150 Hz	175 Hz
Acceleration	1.913	3.823	8.671	12.82	17.741	28.102	
	1.849	3.733	8.784	13.529	16.905	24.142	
	1.974	2.983	8.628	13.442	17.625	26.861	
	1.075	3.527	9.114	14.735	16.925	28.042	
	1.848	3.817	10.074	13.231	15.04	26.097	
				13.239	16.677		
				14.547			
Average	1.726	3.577	9.054	13.649	16.819	26.649	

Table 4.6 BBT point (d = 1 mm, t = 12 mm)

Figure 4.3 BBT curve between frequency and acceleration (d = 1 mm, t = 12 mm)

The relation between the frequency and amplitude of acceleration to cause BBT appears to be proportional in the whole region (Fig. 4.3). But BBT does not occur at frequencies less than 25 Hz, due to the limitation of the shaker. This curve is also a quadratic function has a minimum value at 25 Hz.

From the equation 3-9 and 3-22, the natural frequency (ω_n) scaled is 154.92 rad/s ($f_n = 24.656$ Hz) and kinetic Reynolds number is 38.73.

(Hz)		25	50	75	100	125	150	175
a (g)		1.726	3.577	9.054	13.649	16.819	26.649	None
ω_o/ω_n		1.101	2.028	3.042	4.056	5.07	6.084	7.098
Test	A/r _c	1.372	0.711	0.800	0.678	0.535	0.589	None
Numerical		1.477	0.143	0.268	0.272	0.313	0.435	0.409

Table 4.7 Comparison with Dynamic test and Numerical Method (d = 1 mm, t = 12 mm)

Figure 4.4 BBT curve between Dynamic test and Numerical Method (d = 1 mm, t = 12 mm)

Table 4.7 and Fig. 4.4 compare the experimental data with the mathematical model presented in chapter 3.

Where the ratio between the natural frequency and applied frequency is over 2, test values are bigger than numerical. Numerical graph's minimum point is near 2, but test one is about 5.

4.3.3 Dynamic test ($d = 500 \mu\text{m}$, $t = 1 \text{ mm}$)

In this test, wick whose diameter is $500 \mu\text{m}$ and thickness is 1 mm is used. Applied frequency in the system is 50, 75, 100, 125, 150, 175, and 200 Hz.

Table 4.8 shows that the amplitude level of the acceleration at the burst through in each frequency for a wick diameter of $500 \mu\text{m}$ and thickness of 1 mm .

Frequency	50 Hz	75 Hz	100 Hz	125 Hz	150 Hz	175 Hz	200 Hz
Acceleration	9.137	11.391	10.305	9.114	15.381	16.914	16.6
	9.166	11.502	11.758	9.956	15.024	14.436	18.852
	8.547	10.479	11.248	10.312	13.452	17.386	18.838
	9.842	11.552	11.592	11.389	13.094	14.991	16.025
	10.515	11.529	12.915	9.559	14.579	17.103	14.663
		10.358	12.85	10.515			
		11.152					
		11.042					
Average	9.441	11.126	11.778	10.141	14.306	16.166	16.996

Table 4.8 BBT point ($d = 500 \mu\text{m}$, $t = 1 \text{ mm}$)

This data is displayed graphically in Fig. 4.5.

Figure 4.5 BBT curve between frequency and acceleration ($d = 500 \mu\text{m}$, $t = 1 \text{ mm}$)

From the equation 3-9 and 3-22, the natural frequency (ω_n) scaled is 1039.9 rad/s ($f_n = 165.5 \text{ Hz}$) and kinetic Reynolds number is 67.086. It is assumed that the natural frequency is near 125 Hz and except that region, amplitude of acceleration to cause BBT increases in proportion to frequency (Fig. 4.5).

f (Hz)		50	75	100	125	150	175	200
a (g)		9.441	11.126	11.778	10.066	14.306	16.166	16.996
ω_0/ω_n		0.302	0.453	0.604	0.755	0.906	1.057	1.208
Test	A/r _c	3.754	1.966	1.171	0.640	0.632	0.525	0.422
Numerical		18.195	8.241	4.802	2.979	1.881	1.273	0.87

Table 4.9 Comparison with Dynamic test and Numerical Method ($d = 1 \text{ mm}$, $t = 12 \text{ mm}$)

Table 4.9 and Fig. 4.6 compare the experimental data with the mathematical model presented in chapter 3.

Figure 4.6 BBT curve between Dynamic test and Numerical Method (d = 500 μ m, t = 1 mm)

Test value is lower than numerical where the ratio between w_n and w_o is less than 1.2.

4.3.4 Dynamic test (d = 500 μ m, t = 6 mm)

In this test, wick whose diameter is 500 μ m and thickness is 6 mm is used. Applied frequency in the system is 50, 75, and 100 Hz. Table 4.10 shows that the amplitude level

Frequency	50 Hz	75 Hz	100 Hz
Acceleration	7.843	13.25	19.272
	9.38	12.702	19.613
	6.971	13.58	19.907
	8.889	10.095	22.028
	7.134	10.352	20.597
	10.583	10.322	21.857
		11.906	
		10.36	
Average	8.447	11.571	20.5

Table 4.10 BBT point (d = 500 μ m, t = 6 mm)

of the acceleration at the burst through in each frequency when diameter of wick is 500 μm and thickness is 6 mm. This data is displayed graphically in Fig. 4.7.

Figure 4.7 BBT curve between frequency and acceleration ($d = 500 \mu\text{m}$, $t = 6 \text{ mm}$)

Amplitude of acceleration to cause the BBT is proportioned to frequency in the given region. But this graph is also able to call a quadratic function has minimum value near 50 Hz. Due to the limitation of the displacement in the shaker, BBT can't be acquired less than 50 Hz (Fig. 4.7). From the equation 3-9 and 3-22, the natural frequency (ω_n) scaled is 438.21 rad/s ($f_n = 69.743 \text{ Hz}$) and kinetic Reynolds number is 27.386.

f (Hz)		25	50	75	100	125
a (g)		None	8.447	11.571	20.5	None
ω/ω_n		0.358	0.717	1.075	1.434	1.792
Test	A/rc	None	3.358	2.045	2.038	None
Numerical		13.812	3.541	1.269	0.522	0.223

Table 4.11 Comparison with Dynamic test and Numerical Method ($d = 500 \mu\text{m}$, $t = 6 \text{ mm}$)

Table 4.11 and Fig. 4.8 compare the experimental data with the mathematical model presented in chapter 3.

Figure 4.8 BBT curve between Dynamic test and Numerical Method (d = 500 μ m, t = 6 mm)

Test and numerical values are similar near 1, but test value is little bit higher than numerical where the ratio between w_n and w_o is over 1.5 (Fig. 4.8).

From the results of comparison between test and numerical prediction data (Fig. 4.2, 4.4, 4.6 and 4.8), it is considered that two data are similar around 1.2 ~1.4. Numerical data is higher than measured at the region less than 1.2 and measured data are bigger than numerical where the ratio between w_n and w_o is over 1.4.

4.3.5 Effect of diameter and thickness

To determine the effects of pore diameter, four wicks with the same thickness (1 mm), but different diameters ($d = 1$ mm, 500 μm , 100 μm , and 50 μm) were analyzed. As Equation 3-1 predicts and Table 4.12 experimentally verifies, the capillary pressure required to initiate BBT increases as pore diameter decreases.

Higher amplitude of acceleration is needed for BBT as pore diameter is decreased. With the shaker used, pore diameters of 50 μm and 100 μm required a pressure difference across the wick and vibration simultaneously to initiate BBT.

As examples, 1 mm diameter pore with a vibrating frequency of 100 Hz requires 5.782g to initiate BBT and a 500 μm pore require 11.778g to initiate BBT. In the case of 50 μm and 100 μm diameter pores, BBT does not occur for amplitudes of acceleration up to 15g. For a 100 μm diameter pore with a 0.0419 psi pressure difference, 5.68g is required and for a 50 μm diameter pore with a 0.126 psi pressure difference, 3.44g is required to obtain BBT (Table 4.12).

d (diameter)	1 mm	500 μm	100 μm		50 μm	
A (g) /	5.782	11.778	None	5.688	None	3.44
pressure (psi)	0	0	(Acc. Only)	0.0419	(Acc. Only)	0.126

Table 4.12 Pressure and Amplitude at $f = 100$ Hz required to obtain BBT

Now, consider the effects of various thicknesses. If thickness is increased from 1 mm to 12 mm, a minimum point of a quadratic function is lower. That point is moved from 75 Hz to near 25 Hz (Fig. 4.9). Just consider the amplitude of acceleration to cause BBT higher one is needed over 75 Hz, but it is opposite below than 75 Hz.

That graph (Fig. 4.10) compare with a different thickness ($t = 1 \text{ mm}$ and $t = 6 \text{ mm}$) with same diameter ($d = 500 \text{ }\mu\text{m}$). Higher amplitude of acceleration is needed to get the burst through as the thickness is increased.

These two examples show that, in order to obtain BBT, higher amplitude of acceleration is required when the wick thickness is increased except low frequency region.

Figure 4.9 Effect of thickness ($d = 1 \text{ mm}$)

Figure 4.10 Effect of thickness ($d = 500 \text{ }\mu\text{m}$)

4.3.6 Relationship between the frequency and amplitude

In vibration tests with no external pressure difference, like Fig. 4.11, the amplitude level required for BBT is increased as the external forcing frequency increases (for fixed the diameter and the thickness).

Figure 4.11 Relationship between the frequency and amplitude

But in the low frequency region, due to the limitation of displacement in the shaker BBT point is not able to get and like that reason, BBT points are also not expressed in the graph (Fig. 4.11).

Like Fig. 4.1, Frequency vs. amplitude of acceleration to cause BBT is a quadratic function has a minimum point. As far from this point, it is needed to higher amplitude of acceleration to cause BBT. If a wick with a pore diameter of 1 mm and thickness of 1mm is used as the porous plate for de-watering process, it is recommended to us a 75 Hz as an

applying forcing frequency because it is able to get BBT with relatively small acceleration.

The amplitude level of acceleration to get BBT is needed to higher values as the applying frequency is increased except the resonance region. For a wick has a diameter of 500 μm and thickness of 1 mm, amplitude of acceleration to cause BBT at 125 Hz is less than 100 Hz due to the resonance (Table 4.8 and Fig. 4.12).

Figure 4.12 Relationship between the frequency and amplitude with the resonance

4.3.7 Dynamic test ($d = 100 \mu\text{m}$, $t = 1 \text{ mm}$)

In this test, wick whose diameter is 100 μm and thickness is 1 mm is used. For a 100 μm pore, it is difficult to obtain BBT only utilize a vibration. So, pressure is applied the upper chamber of the wick while the wick is vibrated (Fig. 3.9 and 3.12).

First, 75 Hz is applied in the system with a pressure. Table 4.13 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point.

Pressure (psi)	Acceleration (g)
0.0599	2.826
0.0599	2.949
0.0657	1.638
0.0657	1.226

Table 4.13 BBT point at $f = 75$ Hz ($d = 100 \mu\text{m}$, $t = 1$ mm)

Figure 4.13 BBT curve between pressure and acceleration at 75 Hz ($d = 100 \mu\text{m}$, $t = 1$ mm)

Acceleration of amplitude to cause BBT is reverse proportion in pressure applied upper side of the chamber at the wick. When an applied pressure is 0.06 psi, amplitude of acceleration to cause BBT is about 2.85g and 0.066 psi is needed to 1.4g (Fig. 4.13).

Second, 100 Hz is applied frequency in the system with a pressure.

Pressure (psi)	Acceleration (g)
0.0479	3.759
0.0479	2.471
0.0419	5.485
0.0419	4.875
0.0479	2.662
0.0599	1.415
0.0599	1.348

Table 4.14 BBT point at $f = 100$ Hz ($d = 100$ μ m, $t = 1$ mm)

Table 4.14 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point. This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.14.

Figure 4.14 BBT curve between pressure and acceleration at 100 Hz ($d = 100$ μ m, $t = 1$ mm)

This graph also shows similar trend with Fig. 4.13. Acceleration of amplitude to cause BBT is reverse proportion in pressure applied upper side of the chamber at the wick (Fig 4.14).

Third, 125 Hz is applied frequency in the system with a pressure.

Table 4.15 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point. This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.15.

Pressure (psi)	Acceleration (g)
0.0599	2.503
0.0539	4.075
0.0539	5.286
0.0479	7.356
0.0599	2.173
0.0539	5.923
0.0539	5.292

Table 4.15 BBT point at $f = 125$ Hz ($d = 100 \mu\text{m}$, $t = 1$ mm)

Acceleration of amplitude to cause BBT is also reverse proportion in pressure applied upper side of the chamber at the wick. When the upper chamber's pressure of the wick is 0.048 psi, about 3.7 g is needed to cause BBT while the applied frequency is 100 Hz. In case of 125 Hz, 7.356 g is needed to burst through the meniscus of the wick. Comparing with Fig. 4.14 and 4.15, a decline slope which of data applied 125 Hz is sharper than 150 Hz.

Figure 4.15 BBT curve between pressure and acceleration at 125 Hz (d = 100 μ m, t = 1 mm)

Fourth, 150 Hz is applied frequency in the system with a pressure.

Table 4.16 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point.

Pressure (psi)	Acceleration (g)
0.0539	7.738
0.0599	5.277
0.0539	7.739
0.0539	7.967
0.0539	7.24
0.0419	14.221
0.0359	15.506
0.0657	3.339
0.0539	9.213
0.0599	6.58

Table 4.16 BBT point at f = 150 Hz (d = 100 μ m, t = 1 mm)

Figure 4.16 BBT curve between pressure and acceleration at 150 Hz ($d = 100 \mu\text{m}$, $t = 1 \text{ mm}$)

Acceleration of amplitude to cause BBT is also reverse proportion in pressure applied upper side of the chamber at the wick. In this test to use 150 Hz of applying frequency, BBT is occurred at the pressure less than 0.042 psi. Except this frequency, there is no BBT even though applying acceleration is over 15 g (Fig. 4.16).

Fifth, 175 Hz is applied frequency in the system with a pressure.

Table 4.17 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point. This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.17.

Pressure (psi)	Acceleration (g)
0.0479	10.518
0.0657	4.421
0.0539	3.77
0.0539	5.336
0.0539	6.054
0.0599	3.233
0.0599	4.182
0.0599	4.734
0.0539	7.21
0.0539	6.949

Table 4.17 BBT point at $f = 175$ Hz ($d = 100 \mu\text{m}$, $t = 1$ mm)

Figure 4.17 BBT curve between pressure and acceleration at 175 Hz ($d = 100 \mu\text{m}$, $t = 1$ mm)

Acceleration of amplitude to cause BBT is also reverse proportion in pressure applied upper side of the chamber at the wick. But near the 5 g of acceleration region, data are scatter without a trend curve (Fig. 4.17).

Finally, 200 Hz is applied frequency in the system with a pressure.

Table 4.18 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point. This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.18.

Pressure (psi)	Acceleration (g)
0.0539	12.189
0.0657	3.043
0.0599	4.193
0.0599	4.279
0.0599	5.809
0.0539	7.221
0.0539	7.26
0.0539	7.553
0.0479	12.512

Table 4.18 BBT point at $f = 200$ Hz ($d = 100$ μ m, $t = 1$ mm)

Figure 4.18 BBT curve between pressure and acceleration at 200 Hz ($d = 100$ μ m, $t = 1$ mm)

The relation between the amplitude of acceleration and pressure to cause BBT is similar trends to previous five figures (Fig. 4.13 to 4.17). From those results, it is concluded that

amplitude of acceleration to burst through the meniscus of liquid is reversely proportion in pressure of the upper chamber of the wick.

f (Hz)		75	100	125	150	175	200
a (g)		2.895	0.814	2.190	5.478	3.529	4.500
ω_0/ω_n		0.0878	0.1171	0.1463	0.1756	0.2048	0.2341
Test	A/r_c	0.640	0.101	0.174	0.303	0.118	0.140
Numerical		98.136	55.424	35.654	24.915	18.439	14.332

Table 4.19 Comparison with Dynamic test and Numerical Method ($d = 100 \mu\text{m}$, $t = 1 \text{ mm}$)

Table 4.19 is made from the Table 4.13 to 4.18 and mathematical model. The amplitude of the acceleration value corresponding to 0.06 psi is calculated with linear line supported by excel program.

Figure 4.19 BBT curve between Dynamic test and Numerical Method ($d = 100 \mu\text{m}$, $t = 1 \text{ mm}$)

From the equation 3-9 and 3-22, the natural frequency (ω_n) scaled is 5367.68 rad/s ($f_n = 854.29$ Hz) and kinetic Reynolds number is 13.42.

There is lots of difference between the numerical prediction and measured test data. In the graph, y-direction is log scale. Measured data are scatter and don't show a trend curve like numerical prediction.

4.3.8 Dynamic test ($d = 50 \mu\text{m}$, $t = 1 \text{ mm}$)

In this test, wick whose diameter is $50 \mu\text{m}$ and thickness is 1 mm is used. For a $50 \mu\text{m}$ pore, it is also difficult to obtain BBT only utilize a vibration like a diameter of $100 \mu\text{m}$ pore. So, pressure is applied the upper chamber of the wick while the wick is vibrated (Fig. 3.9 and 3.12).

First, 100 Hz is applied in the system with a pressure.

Table 4.20 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point. This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.20.

Pressure (psi)	Acceleration (g)
0.126	2.32
0.126	4.56

Table 4.20 BBT point at $f = 100 \text{ Hz}$ ($d = 50 \mu\text{m}$, $t = 1 \text{ mm}$)

Figure 4.20 BBT curve between pressure and acceleration at 100 Hz ($d = 50$ μm , $t = 1$ mm)

Like Fig. 4.20, it is very difficult to get BBT even if pressure is also applied inside upper chamber of the wick. The capillary pressure of the wick whose diameter is 50 μm is 0.1317 psi in static condition (Table 4.2). In this test, 0.126 psi of pressure is applied to get BBT. Comparing with previous dynamic test using a diameter of 100 μm , it is needed to apply high pressure which is not much cap with the maximum capillary pressure to get BBT of the wick (Fig. 4.20).

Second, 200 Hz is applied in the system with a pressure. Table 4.21 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point. This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.21.

Pressure (psi)	Acceleration (g)
0.12	1.577
0.12	1.651
0.12	1.169
0.114	3.118
0.126	1.575

Table 4.21 BBT point at $f = 200$ Hz ($d = 50 \mu\text{m}$, $t = 1$ mm)

Figure 4.21 BBT curve between pressure and acceleration at 200 Hz ($d = 50 \mu\text{m}$, $t = 1$ mm)

Like previous dynamic test with diameter of $100 \mu\text{m}$, amplitude of acceleration to burst through the meniscus of liquid is reversely proportion in pressure of the upper chamber of the wick (Fig. 4.21).

Third, 300 Hz is applied in the system with a pressure. Table 4.22 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point.

Pressure (psi)	Acceleration (g)
0.126	1.866
0.126	1.368

Table 4.22 BBT point at $f = 300$ Hz ($d = 50 \mu\text{m}$, $t = 1$ mm)

This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.22.

Figure 4.22 BBT curve between pressure and acceleration at 300 Hz ($d = 50 \mu\text{m}$, $t = 1$ mm)

Like Fig. 4.21, it is needed to about 0.126 psi which is not much cap with the maximum capillary pressure to get BBT of the wick (Fig. 4.22).

Finally, 400 Hz is applied in the system with a pressure. Table 4.23 shows that the amplitude of the acceleration and pressure level of the upper chamber of the wick at the burst through point. This data is displayed graphically with relation between the pressure and acceleration in Fig. 4.23.

Pressure (psi)	Acceleration (g)
0.126	3.76
0.126	3.683

Table 4.23 BBT point at $f = 400$ Hz ($d = 50 \mu\text{m}$, $t = 1$ mm)

Figure 4.23 BBT curve between pressure and acceleration at 400 Hz ($d = 50 \mu\text{m}$, $t = 1$ mm)

From the results of Fig. 4.20 to 4.23, it is concluded that it is very difficult to get BBT without using a high pressure a little bit small than maximum capillary pressure.

From the equation 3-9 and 3-22, the natural frequency (ω_n) scaled is 10733.18 rad/s ($f_n = 1708.24$ Hz) and kinetic Reynolds number is 27.39.

Table 4.24 is made from the Table 4.20 to 4.23 and mathematical modeling. The amplitude of the acceleration value corresponding to 0.126 psi is calculated with linear line supported by excel program.

f (Hz)		100	200	300	400
a (g)		3.44	1.575	1.617	3.722
ω_o/ω_n		0.0585	0.117	0.176	0.234
Test	A/r_c	0.855	0.391	0.179	0.231
Numerical		204.14	51.337	23.041	13.139

Table 4.24 Comparison with Dynamic test and Numerical Method ($d = 50 \mu\text{m}$, $t = 1 \text{ mm}$)

Figure 4.24 BBT curve between Dynamic test and Numerical Method ($d = 50 \mu\text{m}$, $t = 1 \text{ mm}$)

There is also lots of difference between the numerical prediction and measured test data like Fig.4.24. In the graph, y-direction is log scale. Measured data show similar declined trends curve with the numerical prediction.

4.3.9 Relationship between the pressure and amplitude of acceleration

Even though higher amplitude of acceleration is applied to the wick it is not easy to get the burst through due to the higher surface tension in small diameter like a $d = 100 \mu\text{m}$ and $50 \mu\text{m}$. The proper pressure is needed to apply in this case to burst through the meniscus.

For example, in case of $d = 100 \mu\text{m}$, $t = 1 \text{ mm}$, and $f = 100 \text{ Hz}$, there is no burst through when pressure is less than 0.03 psi even if 16.914g is applied in a wick (Fig. 4.14).

When diameter is $50 \mu\text{m}$ and thickness is 1 mm the burst through does not occur in any amplitude if the applying pressure is less than 0.126 psi. Here, maximum capillary is 0.132 psi and there is 0.006 psi gap between two values.

Like these example, it is not easy to get burst through only with the amplitude of acceleration if the diameter is small and the effect of pressure is absolutely important parameter than the amplitude in a small diameter.

5 Conclusions and Recommendations for Future Work

To understand the characteristics of the liquid-gas interface inside the porous screen of a vibro-separator, utilized for the de-watering process, a series of experiments were performed with wick samples having several pores whose diameters range from 50 μm to 1 mm. For these experiments, the wicks were made from Lexan and the pores were produced either using laser machining or mechanical drilling.

Higher amplitude of acceleration is required to obtain bubble burst through as the diameter of the pore is decreased and thickness of the wick is increased. The relationship between the frequency and amplitude of the acceleration to cause the bubble burst through is a quadratic function with a minimum value where BBT can be initiated with relatively small amplitude of acceleration. In the high frequency region, amplitude of acceleration and frequency are proportional to each other. They are inversely related in the low frequency region.

If the pore diameter of the wick is less than 500 μm , it is very difficult to obtain BBT solely utilizing vibration. For these cases, the upper chamber was pressurized and then, the vibration of the plate was able to initiate BBT. The pressure difference across the wick, however, is a more important factor than the amplitude of acceleration.

The correlation between the mathematical model and the experimental BBT data is quite good when there is no applied pressure difference across the wick. Due to the limited range of the shaker used, BBT could be obtained for pore diameters of less than 100 μm only if a pressure difference was applied across the wick. For an imposed pressure difference across the wick, the correlation is not so good.

In the future work, tests should be performed with a vibro-separator that has random pores. Small diameter pores should be tested with a shaker that is able to function at high frequencies, without applying pressure. One way to accomplish this is to use a speaker with a vibrating source. Extending tests to working fluid which have a lower surface tension than water will extend the range of experimental verification and allow BBT to be obtained with a lower amplitude of acceleration.

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