

BUBBLE DYNAMICS IN CONSTANT-FLOW BARBOTAGE

by

MOOSA CHEUNG

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ABSTRACT

In order to improve our understanding of complex boiling heat transfer, there has recently been an increased interest in simulating boiling by barbotage systems (bubbling of a gas into a liquid), as both phenomena are known to promote heat transfer between a heat-transfer surface and a liquid through the stirring of the boundary layer. The present work, in yet further detail, examines and compares bubble hydrodynamics in pool barbotage and saturated pool boiling. The hydrodynamics referred to here are bubble growth (R vs. t , where R is the bubble radius, and t is the growth time), bubble growth rate (dR/dt vs. t), and bubble departure radius.

The present study concentrates exclusively on constant-flow barbotage and nucleate pool boiling as it has been found that certain aspects of bubble growth have more similarities between constant-flow barbotage and boiling bubbles rather than the other limiting case of constant-pressure barbotage bubbles. The barbotage experiments presented in this thesis were devised in which it was possible to compare the hydrodynamics of constant-flow barbotage bubbles with those of nucleate-boiling bubbles reported by Cole and Shulman for the same liquids and the same liquid temperatures. The flow rates for barbotage were chosen to give growth curves (R vs. t) falling, for a substantial portion of the growth time, between the

uppermost and the lowest growth curves for boiling bubbles. (For any one set of fixed boiling conditions, Cole and Shulman show a number of bubble growth curves.) Acetone, methanol, carbon tetrachloride, distilled water, and toluene (the same liquids employed by Cole and Shulman) were used as the experimental liquids and air as the injected gas. Bubble growth and departure radii were determined by high-speed cine photography for all tested liquids and conditions (air flow rates, liquid temperatures and orifice diameters). The experimental results were then quantitatively compared with the constant-flow barbotage theories and nucleate boiling.

The comparisons between the experimental results and the barbotage theories showed:

(i) The experimental growth results were in excellent agreement with the constant-flow bubble growth equation. Thus, it could be concluded that the present apparatus genuinely generated constant-flow barbotage bubbles.

(ii) Bubble departure radii were found to be in good agreement with predictions from the literature with a maximum deviation of $9\frac{1}{2}\%$ in toluene.

For barbotage and boiling, the comparisons indicated:

(i) The bubble growth curves (R vs. t) of the present barbotage experiments had shapes similar to (but not identical to) the boiling results for the same bulk liquid temperatures.

(ii) The bubble growth rates (dR/dt vs. t) of

barbotage bubbles had similar shapes and magnitudes to those of lower boiling bubbles.

(iii) The bubble departure radii of barbotage bubbles fell within the range of those for the boiling bubbles.

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NOMENCLATURE

C	Bubble growth constant (Eqn. 2.11)	
C_p	Specific heat of liquid at constant pressure	J/kg·K
D	Diameter of bubble	m or cm
f	Frequency	sec ⁻¹
g	Acceleration due to gravity	m/sec ² or cm/sec ²
H_{fg}	Latent heat of vaporization	J/kg·K
Ja	Jacob number (Eqn. 2.11)	—
K	Orifice constant	—
M	Virtual mass	kg or gm
P	Pressure	N/m ² or cm Hg
P	Pressure in the plenum chamber	N/m ²
P	Pressure at a large distance	N/m ²
Q	Volumetric air flow rate	ft ³ /hr or cm ³ /sec
R	Radius of bubble	m or cm
T	Temperature	°C or K
t	Time	sec
V	Volume of bubble	m ³ or cm ³

Greek Symbols

ρ	Density	kg/m ³ or g/cm ³
σ	Surface tension	N/m or dynes/cm
θ	Contact angle	degree
α	Thermal diffusivity of liquid	m ² /sec

Subscript

act	Actual flow rate at orifice
b	Bubbling conditions (or conditions at orifice)
d	Departure
eq	Equivalent
e	Expansion stage
F	Final
fb	Force balance at the expansion stage
g	gas
mix	Mixture of air and liquid vapor
I	Indicated air flow rate
l	Liquid
m	Metering conditions
o	Orifice
sat	Saturation temperature of liquid
v,vap	Vapor
w	Wall (or surface)

CHAPTER 1

INTRODUCTION

1.1 Background

Pool barbotage is the bubbling of a gas through an immersed orifice or porous surface into a pool of initially stationary liquid. Pool boiling is boiling on a heater surface submerged in a pool of initially stationary liquid. One common type of pool boiling is nucleate boiling which is characterized by the growth of bubbles in a liquid at specific points on an immersed hot solid surface with the temperature sufficiently greater than the saturation temperature of the liquid. The relation between boiling and barbotage is of great interest as both phenomena are known to promote heat transfer between a heat-transfer surface and a liquid through a bubble-stirred boundary layer.

In general, there are two limiting types of flow in barbotage systems. One case, commonly referred to as the "constant-flow" case, pertains to bubble formation in which the rate of gas flow into a bubble is essentially constant. The other limiting case, referred to as the "constant-pressure" case, pertains to bubble formation at an orifice which is supplied with gas from an ante-chamber at constant pressure. A more detailed discussion of these two limiting cases will be given in Chapter 2, Literature Review.

Barbotage systems are attractive for the study of

bubble-stirred boundary layers because, in contrast with boiling, the generation rate of a barbotage system is independent of the rate of heat transfer and can be accurately controlled and measured. Further, in boiling, there are heat transfer mechanisms involving both latent heat and agitation effects while in barbotage only agitation effects are present. Agitation effects in both barbotage and boiling are related to bubble hydrodynamics: generally speaking, the phenomena associated with bubble growth and departure. Since only agitation effects are present in barbotage systems, this can be an advantageous simplification; thus barbotage studies should help to improve the understanding of heat transfer across bubble-stirred boundary layers and hopefully shed additional light on the mechanisms in boiling.

When simulating nucleate boiling by barbotage, the aspects considered may be purely hydrodynamic, or may include heat transfer. As regards hydrodynamics, the similarities in appearance of flow regimes in barbotage and saturated nucleate boiling have been noted[43,44,49]; the similarities of bubble formation with time have also been pointed out[37,43]. Some investigators[2,35,44] have used barbotage to simulate the critical heat flux. With respect to heat transfer, the average heat-transfer coefficients in both boiling and barbotage have been compared[2,50,51]. Barakat and Sims[4,5] have compared the instantaneous heat-transfer coefficients and liquid flow patterns in pool boiling and pool barbotage, commenting on the similarities

and dissimilarities. They have also shown, through the examination of bubble growth behavior that there is more similarity between boiling bubbles and barbotage bubbles under constant-flow conditions rather than constant-pressure conditions. It should be noted that the constant-flow barbotage bubbles generated by Barakat and Sims[5] for the heat transfer comparison were at very small gas flow rates ($< 1.0 \text{ cm}^3/\text{sec}$); the departure sizes of the barbotage bubbles were considerably smaller than the specific boiling bubbles in the comparison and the barbotage bubble growth times were longer. The liquid under consideration was toluene.

The present work attempted to answer the question: "How well can the hydrodynamics of boiling bubbles be simulated by barbotage bubbles using a simple system, namely constant-flow barbotage?" The hydrodynamic phenomena studied here were bubble growth (R vs. t , where R is the bubble radius, and t is the bubble growth time), bubble growth rate (dR/dt vs. t), and bubble departure radius. These are no doubt important in determining agitation effects. The approach was to find boiling results in saturated nucleate pool boiling which would allow for the operation of the barbotage system at atmosphere pressure. (It was desired to run at the same liquid temperatures as those for boiling in order to obtain similar liquid properties). An excellent set of boiling results was available in the work of Cole and Shulman[6] who showed a number of bubbles for nominally the same conditions in

different liquids; for each bubble they also showed a complete growth curve (R vs. t) from bubble initiation to bubble break-off radius. Their results were generally at sub-atmospheric pressures, allowing in a number of cases, by virtue of the low saturation temperatures, the corresponding barbotage systems to be run at room temperature or some degrees above room temperature at atmospheric pressure.

For the longer term, if the hydrodynamics of boiling bubbles can be more closely simulated by barbotage systems, heat transfer experiments similar to those of Barakat and Sims[5] could be repeated.

1.2 Purpose and Scope

The present study concentrates exclusively on constant-flow barbotage and nucleate boiling. The objectives of the study were:

(i) to conduct experiments in different liquids to determine the bubble growth and bubble departure radii of constant-flow barbotage under conditions such as to compare with certain of the boiling results reported by Cole and Shulman[6],

(ii) to compare the above barbotage experimental results with the bubble growth equation and theoretical predictions of bubble departure radii based on the model of Kumar and Kuloor[22].

For comparison of the hydrodynamics between boiling

and the present barbotage results, gas flow rates, based on the barbotage bubble growth equation, were chosen to give growth curves (R vs. t) falling, for most of the growth time, roughly mid-way between the uppermost and the lowest bubble growth curves for the boiling results of Cole and Shulman[6]. (It should be kept in mind that Cole and Shulman indicate a large variation in bubble growth, R vs. t for a fixed set of conditions.) The liquids used were acetone, methanol, carbon tetrachloride, distilled water, and toluene. The temperatures of the liquids used in the present investigation were essentially the same as the saturation temperatures corresponding to the pressures stated by Cole and Shulman, thereby obtaining similar liquid properties for both barbotage and boiling. Air was used as the bubbling gas. Orifice diameters of 0.3 cm, 0.4 cm, and 0.6 cm were used.

1.3 Layout of Thesis

A literature review on bubble hydrodynamics in pool barbotage and nucleate pool boiling is presented in Chapter 2. Chapter 3 gives details of the experimental apparatus, and photographic equipment while Chapter 4 covers the experimental procedures and conditions. Chapter 5 includes the results and discussion and is divided into three main parts as follows:

- (i) Bubble behavior,
- (ii) Bubble growth and departure size,
- (iii) Comparison of present barbotage and nucleate-

boiling bubble hydrodynamics.

The summary and conclusions are presented in Chapter 6. Repeatability tests, calibration of the rotameter, physical properties of experimental liquids, calculation of bubble volume, calculation of actual flow rate at the orifice, and bubble identification and tabulated data are presented in appendices.

The general behavior of barbotage bubbles is shown in Figs. 5.1 and 5.2; the bubble type observed is summarized in Table 5.1. The bubble growth results in different liquids and conditions are given in Figs. 5.3 through 5.11 while the comparison of experimental results and bubble growth equation is presented in Figs. 5.12 to 5.20. Table 5.3 summarizes the comparison of experimental bubble departure radii with theoretical predictions from the literature. Figures 5.21 to 5.30 and Table 5.4 give comparisons of the hydrodynamics between the present barbotage and boiling bubbles in terms of the bubble growth (R vs. t), bubble growth rate (dR/dt vs. t), and bubble departure radius.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 Barbotage Dynamics

2.1.1 Introductory remarks

As a barbotage bubble is formed by the flow of a gas through an upward-facing orifice above a gas chamber (sometimes also called an ante-chamber), the pressure within the bubble changes with time. If the pressure beneath the orifice is constant, the gas flow rate will vary with time. If there is a high pressure drop restriction, such as a very long thin capillary, between the orifice and gas chamber, the pressure fluctuations due to the forming bubbles are much smaller than the pressure drop between the orifice and the gas chamber. In this case, the gas flow rate can be treated as a constant, a limiting case. If the volume of the gas chamber upstream of the orifice is very large by comparison with the volume of bubble being formed and if the pressure drop across the orifice is small, the situation corresponds to the other limiting case of bubble formation under constant-pressure-supply conditions. For conditions intermediate between the limits of constant flow rate and constant pressure, the chamber volume must be taken into account. The phenomenon of bubble formation under these various conditions was first reported by Hughes et al.[19]

and later thoroughly reviewed by Park[26], and by Kumar and Kuloor[22]. The following review keeps the emphasis more on barbotage bubble formation under constant-flow-rate conditions than on barbotage under constant-pressure-supply and intermediate conditions. The review is made under two separate headings, namely, 'bubble growth rate' and 'bubble departure size'.

2.1.2 Bubble growth rate

Bubble formation from a submerged orifice under constant-flow-rate conditions can be achieved by passing the gas through a long thin capillary in line with the orifice or through a porous plate attached to the underside of the orifice plate. The pressure drop across the capillary or porous plate is very large so that the pressure fluctuations within the bubbles due to changes in the radius of curvature have a negligible effect on the gas flow rate. Since the gas flow in this case is constant, the bubble growth is, therefore, simply expressed as

$$dv/dt = Q, \quad 2.1$$

where V=volume of the bubble,

t=time,

Q=gas flow rate.

If the bubble volume throughout the period of growth is assumed to be of a spherical shape, then Eqn. 2.1 can be written as

$$\frac{d}{dt} \left(\frac{4}{3} \pi R^3 \right) = Q \quad 2.2$$

where R is the radius of the bubble. Rearranging Eqn. 2.2 gives

$$\frac{dR}{dt} = \frac{Q}{4\pi R^2} \quad 2.3$$

The integration of Eqn. 2.3 with $R=0$ at $t=0$ as initial condition would yield

$$R = \left(\frac{3Q}{4\pi}\right)^{1/3} t^{1/3} \quad 2.4$$

Substitution of R from this equation in Eqn. 2.3 gives

$$\frac{dR}{dt} = 0.2068Q^{1/3} t^{-2/3} \quad 2.5$$

Equations 2.4 and 2.5 are to be used to compare with the present investigation of constant-flow barbotage in the five different liquids mentioned earlier in Chapter 1.

For the other limiting case of bubble formation under constant-pressure conditions, bubble growth is more complicated as compared with bubble growth under constant-flow conditions. In the constant-pressure case, the small pressure drop across the orifice, coupled with the changing pressure in the bubble and the constant plenum chamber pressure, results in a changing gas flow rate during the entire period of bubble growth.

Subash and Sims[37] formulated a bubble growth equation under constant-pressure conditions by combining the equation of motion for an expanding bubble (the Rayleigh equation [29]) with the orifice equation. The result of the

formulation is given in the following dimensionless relation:

$$R^* \ddot{R}^* + 1.5 \dot{R}^{*2} + 8ER^{*4} \dot{R}^{*2} + \frac{2}{R^*} = 2\Delta P^* \quad 2.6$$

where $R^* \equiv \frac{R}{R_0}$,

$$\dot{R}^* \equiv \frac{dR^*}{dt^*},$$

$$\ddot{R}^* \equiv \frac{d}{dt^*} \left(\frac{dR^*}{dt^*} \right),$$

$$t^* \equiv t \left[\frac{\sigma}{\rho_L R_0^3} \right]^{\frac{1}{2}},$$

$$\Delta P^* \equiv \frac{\Delta P}{\Delta P_{crit}} \equiv \left[\frac{p_1 - p_\infty}{\frac{2\sigma}{R_0}} \right],$$

$$E = \frac{1}{(K)^2} \frac{\rho_g}{\rho_L},$$

R =radius of the bubble,

R_0 =radius of the orifice,

K = orifice constant,

p_1 =Pressure in the plenum chamber,

p_∞ =pressure at a large distance from the bubble at the level of the orifice,

t =time,

σ =surface tension,

ρ_g =gas density,

ρ_L =liquid density.

The solution of Eqn. 2.6 can be carried out by numerical integration, using the fourth order Runge-Kutta formula with conditions at time $t=0$,

$$R^*(0)=1$$

$$\dot{R}^*(0)=0$$

The bubble growth rates predicted by Eqn. 2.6 have been found to be in good agreement with the experimental data for water, acetone, and hexane. The complete derivation of Eqn. 2.6 is contained in Subash and Sims[37].

A survey of barbotage literature indicated that, so far, the analytical solution to bubble growth under intermediate conditions has not yet been available.

2.1.3 Bubble departure size

The determination of bubble departure volume (also called the 'terminal bubble volume') is strongly dependent on the gas flow rate in the constant-flow-rate case. In addition, orifice size, surface tension, liquid density, and liquid viscosity have been found to be the most important factors influencing the bubble departure size. A good review of the literature on the above-mentioned factors which influence the bubble departure size was presented by Kumar and Kuloor[22]. The theoretical predictions of bubble departure size under constant-flow-rate conditions are briefly discussed below.

Since the liquids involved in the present investigation have small viscosities (≤ 1.0 cp), emphasis will be placed on the theoretical predictions of bubble departure size for inviscid liquids while for viscous liquids, the reader is referred to Refs.[10,22].

At very small flow rates ($\leq 1.0 \text{ cm}^3/\text{sec}$) [22,23], the bubble departure volume can be determined when the upward buoyant force is balanced by the downward force due to surface tension. The balance of these two static forces, therefore, directly gives the departure bubble volume as

$$V_d = \frac{\pi D_o \sigma \cos \theta}{g(\rho_l - \rho_g)} \quad 2.7$$

where V_d = bubble departure volume,
 D_o = orifice diameter,
 θ = contact angle,
 g = gravitational acceleration

The contact angle here is defined as the angle between the vertical and the stretched interface at the base of the bubble.

As the flow rate is increased, the liquid inertial force which is associated with the gas flow rate becomes significant. For small orifice sizes, Davidson and Schüller[11], assuming the bubble to be forming at a point source where the gas is supplied, have developed a simple theoretical equation considering only buoyant and liquid inertial forces. This equation is given by

$$V_d = 1.378 \frac{Q^{6/5}}{g^{3/5}} \quad 2.8$$

where V_d is the bubble departure volume and Q is the gas flow rate. Eqn. 2.8 has been used to verify bubble departure volumes obtained for flow rates up to $3.0 \text{ cm}^3/\text{sec}$ and orifice radii from 0.0143 to 0.0334 cm. Davidson and

Schüler[11] find that theory and experiment agree excellently only in the flow range of 1.5 to 3.0 cm³/sec. For larger orifices, Davidson and Schüler have also developed another equation which takes into consideration the residual bubble that forms the nucleus of the succeeding bubble. However, this equation has been compared with their experimental values obtained for larger orifices (0.15 to 0.25 cm in radii) and found to have considerable deviation for flow rates beyond 20.0 cm³/sec.

Kumar and Kuloor[22] assume bubble formation takes place in two stages, namely, the expansion stage and detachment stage. The bubble is assumed to stay at the orifice in the first stage, whereas in the second stage it is assumed to travel away from the orifice until it detaches itself. An idealized sequence of bubble formation according to the theoretical prediction of Kumar and Kuloor[22] is shown in Fig. 2.1. At the end of the expansion stage, they consider that the bubble volume is determined by the balance between the upward buoyancy and the downward surface tension and inertial forces, for this situation, the bubble volume is expressed as

$$V_{fb} - \frac{11Q^2 V_{fb}^{2/3}}{192\pi (3/4\pi)^{2/3} g} = \frac{\pi D_o \sigma \cos\theta}{\rho_l g} \quad 2.9$$

where V_{fb} = volume of bubble at the end of the expansion stage, and the other symbols are as introduced earlier. During the detachment stage, the bubble moves upward while

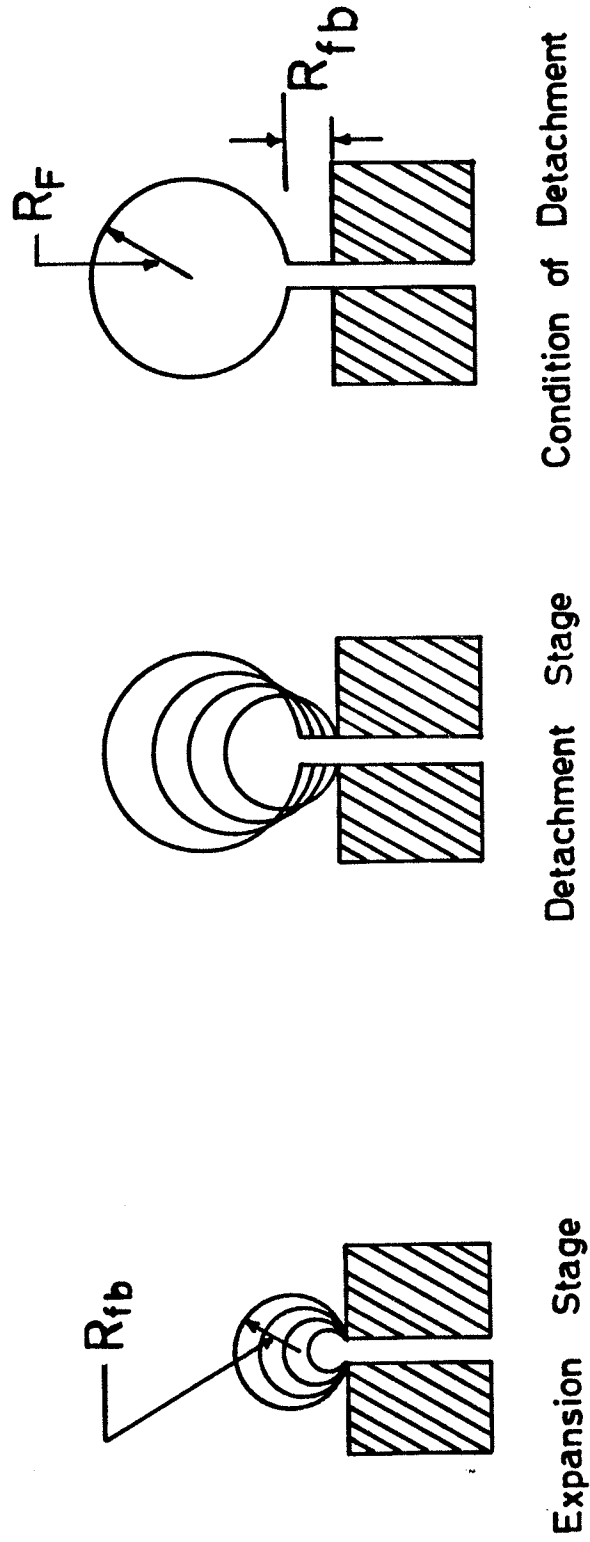


Fig. 2.1 Idealized Sequence of Bubble Formation.

growing and attaches to the orifice by a neck as shown in Fig. 2.1; the bubble detaches when its base has moved a distance equal to the radius (R_{fb}) of the bubble volume at the end of the expansion stage. From the Newton's second law of motion, they obtain the equation of the final bubble volume at the end of the detachment stage. The equation is given as

$$R_{fb} = \frac{P}{4Q}(V_F^2 - V_{fb}^2) - \frac{9N}{Q}(V_F^{1/3} - V_{fb}^{1/3}) - \frac{J}{Q}(V_F - V_{fb}) \\ + \frac{1}{Q} \left[(JV_{fb} + 3NV_{fb}^{1/3} - \frac{P}{2}V_{fb}^2) \right] (\ln V_F - \ln V_{fb}) \quad 2.10$$

where $P = \frac{16g}{11Q}$,

$$J = \frac{16\pi D_o \sigma \cos \theta}{11Q\rho_l},$$

$$N = \frac{Q}{12\pi(3/4\pi)^{2/3}},$$

V_F = final bubble volume,

R_{fb} = radius of bubble at the end of the expansion stage.

It should be noted that the gas density in both Eqns. 2.9 and 2.10 does not appear since it is assumed to be negligible in comparison with the liquid density (i.e. From Eqn. 2.10, the final bubble volume, V_F can be calculated by iteration. The value of R_{fb} to be used in Eqn. 2.10 is evaluated from the expansion stage, i.e. from Eqn. 2.9 with $\cos \theta$ taken as unity.

The above equations have been verified by Kumar and

Kuloor[22] with their own experiments and with experimental data including those experiments of Davidson and Schüller[11] and Datta et al.[8]; the theoretical values of bubble departure diameter are in good agreement with the experimental data. Equation 2.10, with R_{fB} from Eqn. 2.9 will be used for comparison with the experimental results in the present investigation.

2.2 Nucleate Boiling Dynamics

2.2.1 Introductory remarks

Nucleate pool boiling occurs when a heater is submerged in a pool of initially stationary liquid. When the surface temperature of the heater sufficiently exceeds the saturation temperature of the liquid, vapor bubbles grow rapidly in the superheated liquid layer next to the surface until they depart and move out into the bulk liquid while rising as the result of buoyancy. If the bulk liquid is subcooled the bubbles collapse. Thus in nucleate boiling a complex fluid motion around the heater is initiated and maintained by the nucleation, growth, departure and collapse of bubbles as well to some degree by natural convection.

Good reviews of boiling bubble dynamics can be found in Refs.[18,30,40,42]. The bubble growth rate of nucleate pool boiling is briefly discussed below.

2.2.2 Bubble growth rate

The bubble growth period can be divided into three regions, namely the dynamically controlled region which occurs in the very early stage of bubble growth, the thermally controlled region in the later stage of bubble growth and the transition region where both dynamic and thermal effects can be important. The motion in the dynamically controlled region can be described by the Rayleigh solution[29]. The classical analyses, e.g.[12,13,27], have as a result for the thermally controlled region in a uniformly superheated liquid of infinite extent, that the bubble radius increases with the square root of time. The equation is of the form

$$R = 2CJa\sqrt{\alpha t} \quad 2.11$$

where C = growth constant,

α = thermal diffusivity of the liquid,

$$Ja \equiv \frac{C_p \rho_l (T_w - T_{sat})}{H_{fg} \rho_v},$$

C_p = specific heat at constant pressure,

T_w = wall temperature at superheated conditions,

T_{sat} = saturation temperature of the liquid,

H_{fg} = latent heat of vaporization of the liquid.

The values of the growth constant, C given by Fritz and Ende[13], Forster and Zuber[12], and Plesset and Zwick[27] are $\sqrt{1/\pi}$, $\sqrt{\pi/2}$, and $\sqrt{3/\pi}$ respectively. Of special interest in the current investigation, Cole and Shulman[6] correlated

their experimental data for water and organic liquids at a heat transfer surface in saturated nucleate pool boiling by the expression

$$R = 2.5Ja^{3/4}\sqrt{\alpha t} \quad 2.12$$

In most practical situations, by far the major portion of bubble life is in the thermally controlled region.

As regards experimental data, especially for bubble growth at a heating surface, besides the radius increasing with a time exponent of $1/2$, one sees other values of this exponent as well. Westwater et al.[46], fitting their bubble growth results in the form $R \sim t^n$ for pentane and ether, found that the mean time exponent, n , varied from 0.190 to 0.525. Akiyama et al.[1] studied the effect of system pressure on the growth characteristics of an isolated vapor bubble using water, ethanol and carbon tetrachloride. They found that in the large pressure region (1.0 to 30.0 atm.), the time exponent decreased roughly from 0.5 to nearly 0.1 for water, while in the low pressure region (0.4 to 1.0 atm.), the time exponents for the three liquids ranged from 0.4 to 1.0. Subash and Sims[37] used a least-squares analysis to obtain the time exponents for some experimental bubble growth data published by various investigators[15,16,21, 36,41] for saturated nucleate boiling of water at atmospheric pressure. They found that the time exponents ranged from 0.33 to 0.64.

It is understood that there are some situations,

especially in the boiling of liquid metals, where the transition region (both dynamic and thermal effects need to be considered) is important. Work such as that of Mikic et al.[25] and Theofanous et al.[38] pay special attention to this region.

2.3 Barbotage as an Analog of Boiling

In this section the existing literature comparing the bubble growth rates in barbotage and boiling will be briefly discussed. Zuber[49] considered Davidson and Amick's[9] description of the appearance of barbotage bubbles forming at an orifice under constant flow rate conditions and noted that the description fitted well the formation in Yamagata and Nishikawa's[48] experiments in nucleate boiling. Wallis[43] compared the bubble growth rate of Siemes and Kauffmann[33] for the constant-flow-rate case in barbotage to Stanizewski's[36] boiling growth rate results for water at atmospheric pressure; he concluded that the (volumetric) growth process in both cases was linear in nature during the major part of a bubble's history. Subash and Sims[37] indicated that the experimental bubble growth rate results in boiling appeared to fall between the growth rate results determined for the two limiting cases of barbotage, viz, the constant-flow case and constant-pressure case. Recently, Barakat[3] has compared barbotage with the boiling data of Cooper and Lloyd[7] for toluene and illustrated the similarity of the bubble growth behavior between boiling bubbles and constant-flow barbotage bubbles.

CHAPTER 3

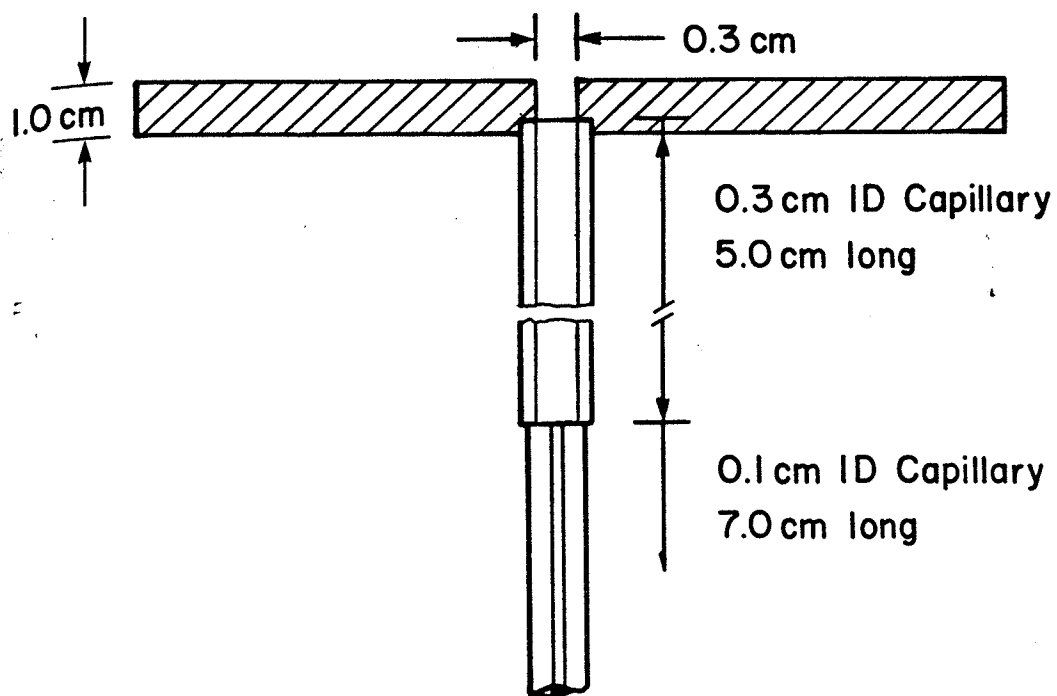
APPARATUS

3.1 Introductory Remarks

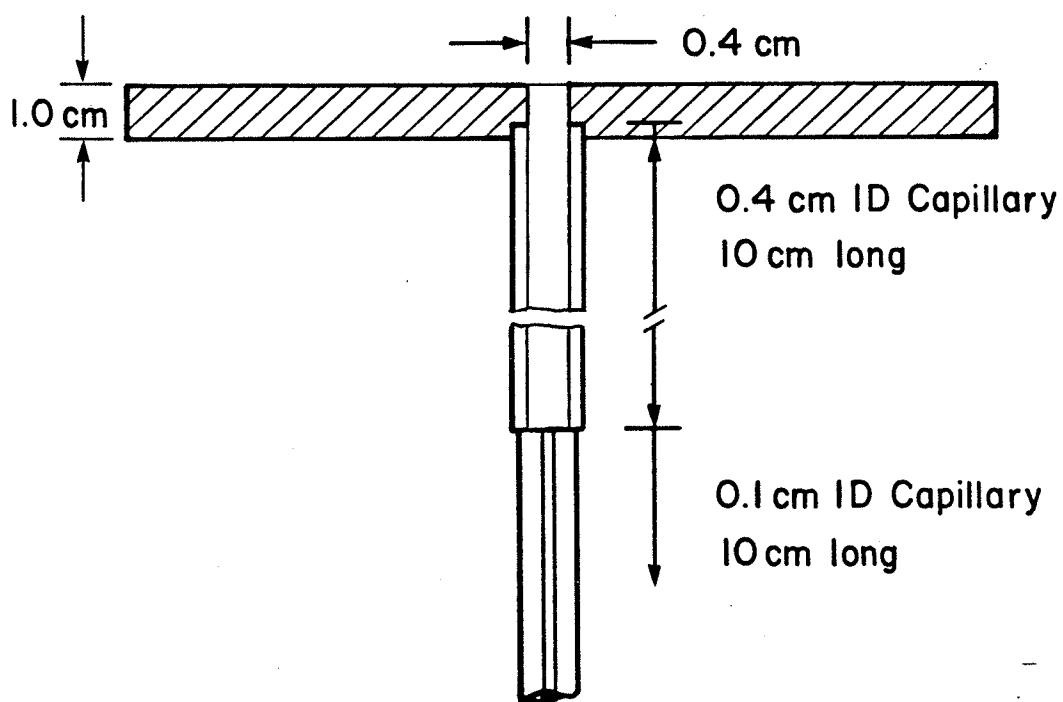
The experimental apparatus used in the present work was designed to measure the growth of barbotage bubbles formed at submerged orifices of different sizes under constant flow conditions for different air-liquid systems. The apparatus can be divided into three major components, namely, the test section, air-supply system, and photographic equipment.

3.2 Test Section

The test section essentially consisted of an orifice plate, capillary tube and bubbling tank. The orifice plate arrangements are shown in Fig. 3.1. Three identical circular plates were made of stainless steel, each with a diameter of 16.8 cm and a thickness of 1.0 cm. An orifice was drilled in the centre of each plate. The orifice diameters of the three plates were 0.3 cm, 0.4 cm, and 0.6 cm. For orifice diameters of 0.3 cm and 0.4 cm with lower gas flow rates, the capillary was divided into two sections. The upper section of the capillary that was directly glued to the plate in line with the orifice and had the same internal diameter as the orifice, while the lower section of the capillary had an internal diameter smaller than the orifice to ensure a large pressure drop for obtaining constant-flow-rate conditions. The arrangement for the

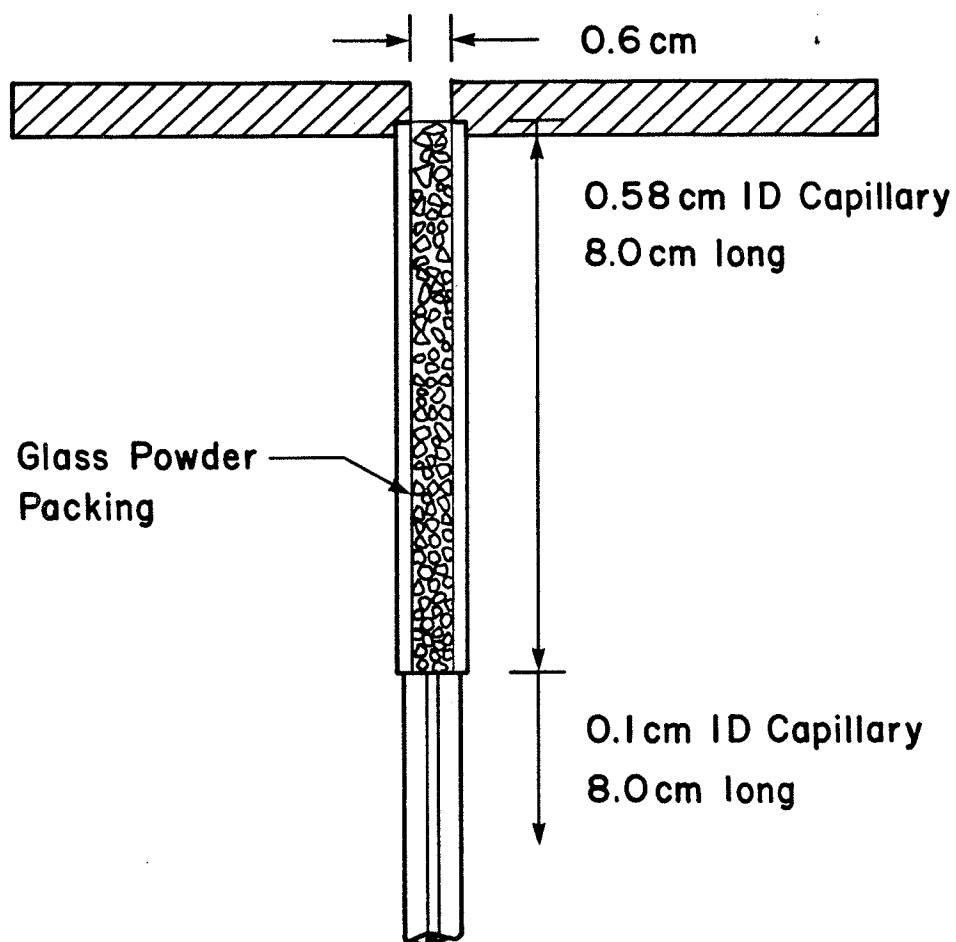


(A) 0.3 cm Orifice plate



(B) 0.4 cm Orifice plate

Fig. 3.1 Orifice Plate Arrangements.



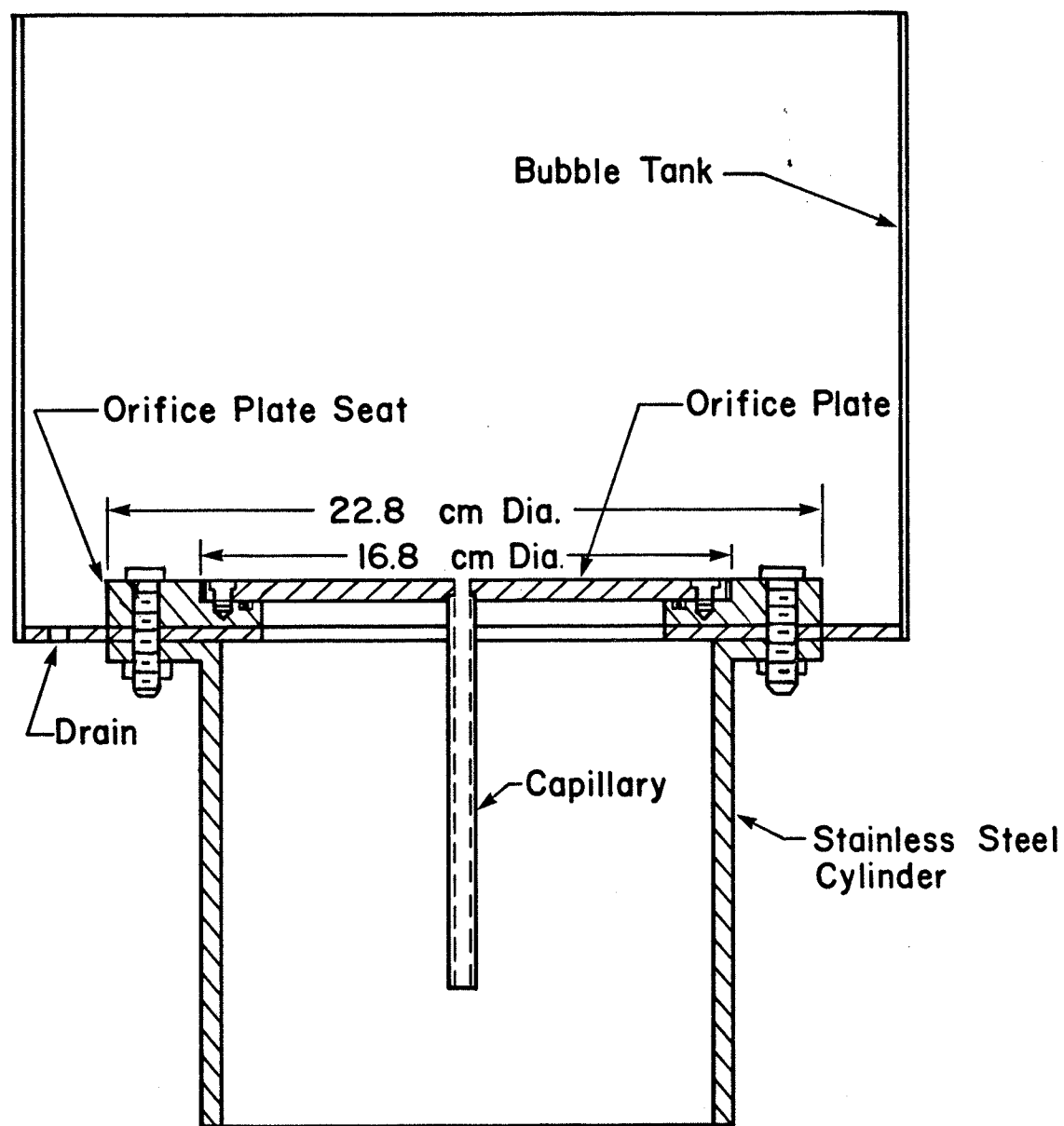
(C) 0.6 cm Orifice Plate

larger orifice diameter of 0.6 cm with higher gas flow rates was basically the same as those for the smaller orifices except the upper section of the capillary was packed with glass powder to make certain that a large pressure drop was achieved. The complete test section is shown in Fig. 3.2. The bubbling tank was made by bonding four glass plates of identical dimensions to the four sides of a 0.48 cm thick brass plate which formed the bottom of the tank. The inside dimensions of the tank were 25 cm x 25 cm x 20 cm. The hollow stainless steel cylinder served as a support for the bubbling tank and accommodation for the capillary tubes. For experimental runs at liquid temperatures higher than room temperature, the whole bubbling unit was immersed in a water bath tank which was a glass tank, 40.6 cm x 38.1 cm x 30.5 cm with a brass base. The left and right sides of the water bath were insulated to minimize the heat loss from the water bath to the surroundings while the rear and front were left uninsulated for photographic purposes.

3.3 Air Supply System

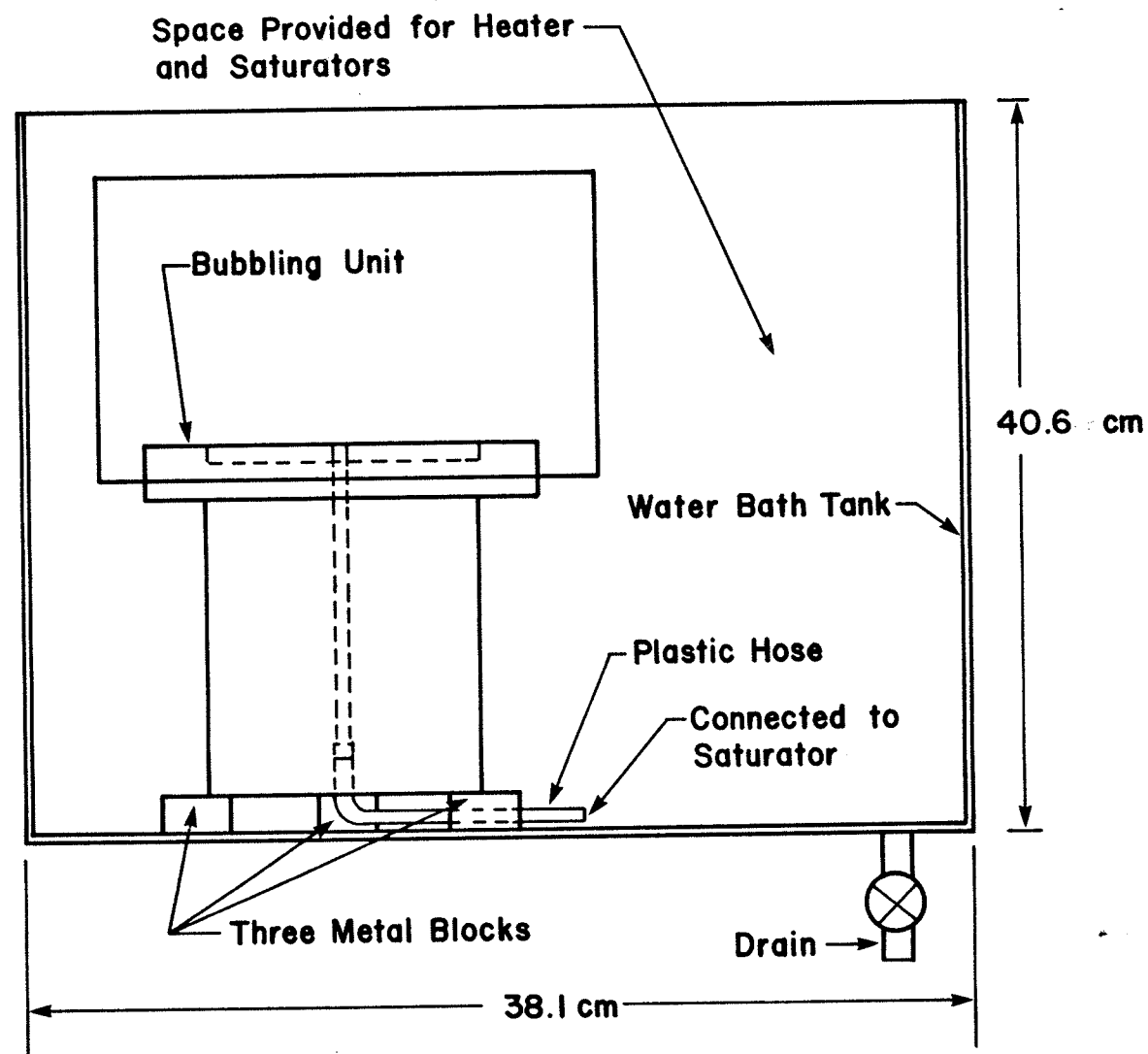
Figure 3.3 shows a schematic of the air supply system which consisted of a pressure regulator, filter, dryer, flow meter (rotameter), pressure gauge, saturators and a heater (used only for those experiments conducted at temperatures higher than room temperature).

Air was supplied from the building air compressor operating between 80 psig (552 kPa) and 100 psig (690 kPa) and reduced in pressure to the experimental operating



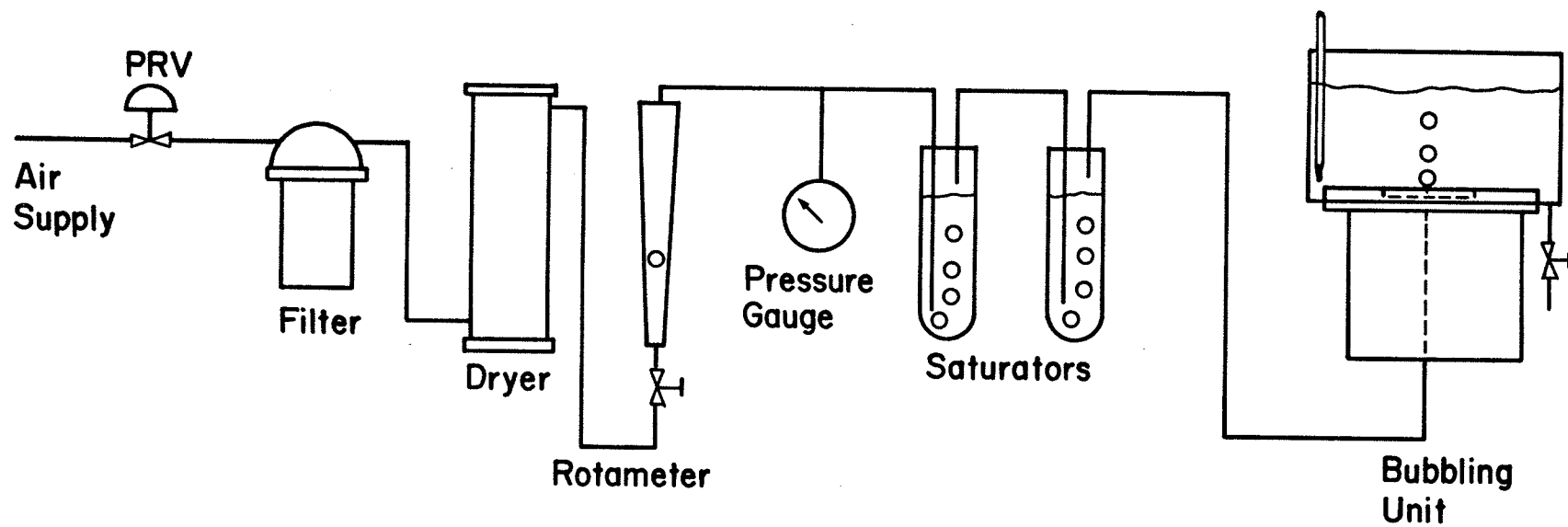
(A) For Room-temperature Experiments

Fig. 3.2 Test Section Arrangement.



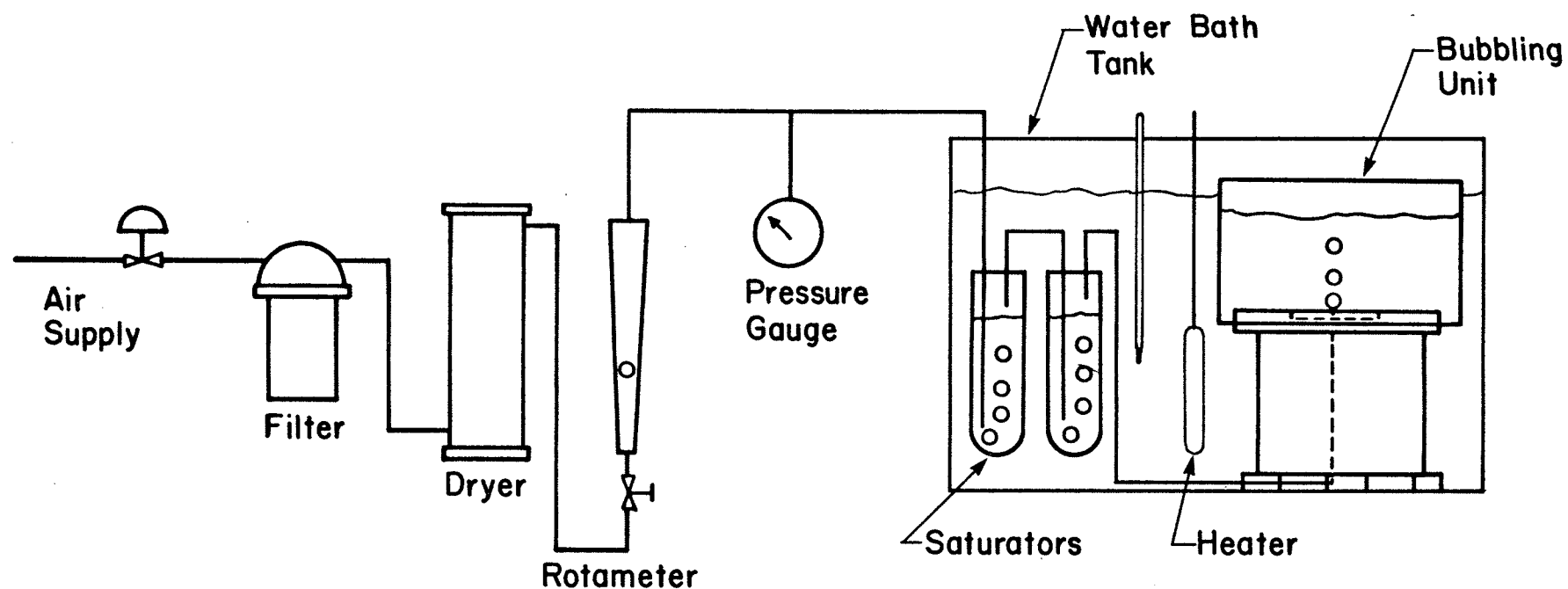
(B) For Higher-temperature Experiments

Fig. 3.2- (Cont.) Test Section Arrangement.



(A) Arrangement for Room-temperature Experiments

Fig. 3.3 Schematic of Air Supply and Bubbling Unit.



(B) Arrangement for Higher-temperature Experiments

Fig. 3,3 (Cont.) Schematic of Air Supply and Bubbling Unit.

condition in passing through the pressure regulator valve. As the air passed through the filter and the gas dryer, oil particles, dust and moisture present in the air were removed. Next, the air passed through the flow meter (Brooks Instrument Canada Ltd., Model No. 1560) which had a built-in needle valve to control accurately the flow range up to $125 \text{ cm}^3/\text{sec}$. The air was saturated with the vapor of the liquid in passing through two saturators containing that liquid. Finally, the air passed through the capillary and orifice into the bubbling tank containing the experimental liquid. The line pressure between the flow meter and the saturators was measured by a pressure gauge for calculation of the air flow rate at the flow meter to be corrected subsequently for conditions at the orifice. For experimental runs with liquid temperatures higher than room temperature, a 500-watt (at 115 volts) General Electric Hot Point immersion heater was used, at variable voltage in the water bath surrounding the bubbling unit (as shown in Fig. 3.3b), thus raising the air and the liquid pool temperature to the required value.

The flow meter was calibrated before running the experiments. The calibration method and procedure are presented in Appendix B.

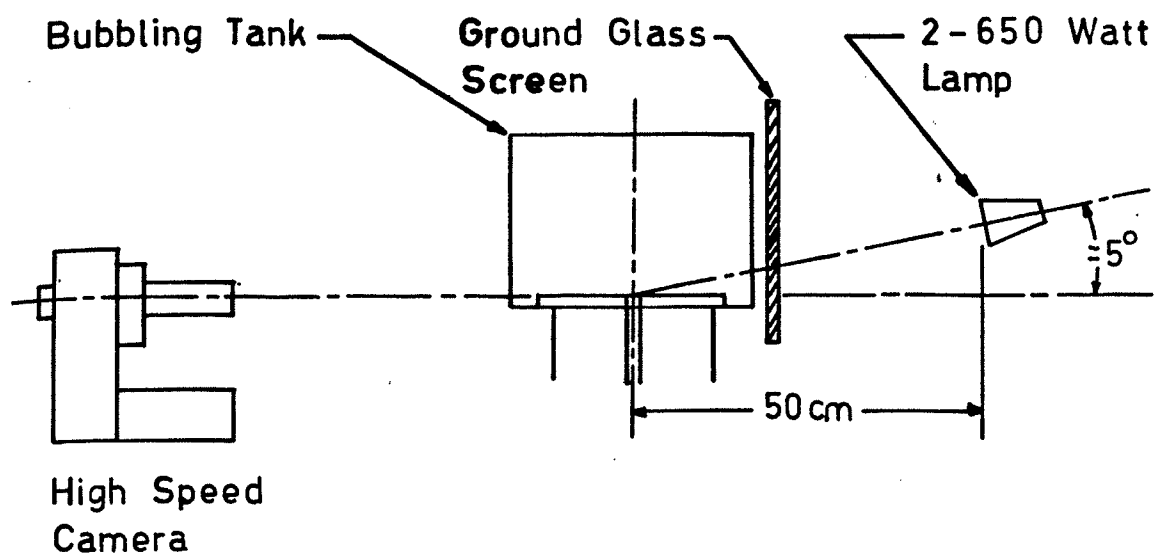
3.4 Photographic Equipment

A Hycam Model 41-0004 16mm high-speed motion picture camera with a speed range of 10-11000 frames per second was used. The air bubbles were photographed using as the

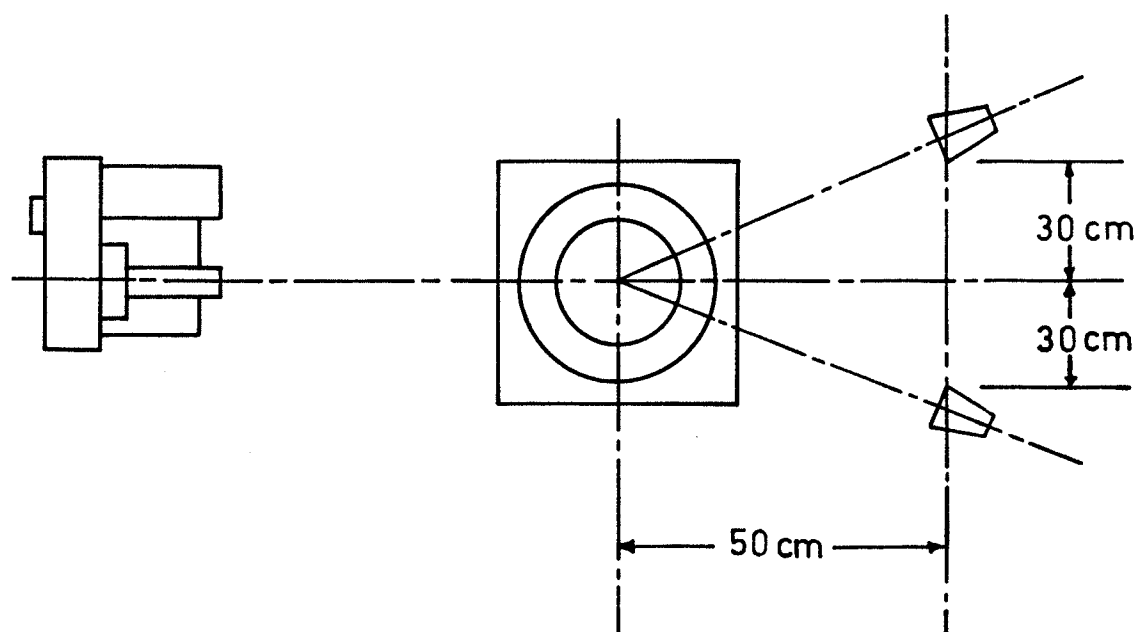
objective lens a Cosmimar 4 in. focal length, $f/2.5$ with 30 mm 'C' mount extension. The camera was equipped with two built-in timing lights. One light generating at 100 pulses/sec was used to obtain the frame speed. The film stock was Kodak 16mm, Ektachrome, VNX 430.7250, colour film in 100-ft rolls. The camera was located at a distance from the orifice plane, such that the field-of-view was slightly larger than the size of the terminal bubbles forming at the orifice. Before the filming began, the camera was focussed on a wire placed in the centre of the orifice. Two 650 watt (at 115 volts) lamps were used in conjunction with a ground glass screen to provide illumination for the photography. The light arrangement resulting in sharply defined bubble profiles is shown in Fig. 3.4, and was based on the experience of Subash and Sims[37] and Barakat[3]. To choose the correct combination of the film speed (ASA 400), f -stop, and camera speed, a Pentax Spotmeter III was used.

In order to determine the true volume of a bubble from a magnified image, a stainless steel rod whose actual diameter was known was suspended above the orifice vertically, and its image recorded at 500 frames/sec. The actual diameter of the rod was 0.955 cm.

The developed photographic films were projected frame by frame on a PCD Model 2AE-3A Viewer equipped with a digital X-Y reader which enabled the accurate measurement of bubble volumes and bubble formation times. A Goodkin projector with an objective lens having a focal length of



Elevation



Plan View

Fig. 3.4 Arrangement of Photographic Equipment.

150 mm was employed to enlarge the figures of boiling data of Cole and Shulman[6] for the accurate measurement of their bubble growth results which were to be used later to compare with those of the present barbotage bubbles.

CHAPTER 4

PROCEDURE

4.1 Introductory Remarks

Before running the experiments, some air flow rates based on Eqn. 2.4 were chosen to generate growth curves (R vs. t) which fell within the band of boiling results, for fixed conditions, of Cole and Shulman[6] while the others were selected arbitrarily. High-speed cine photography was used to record the detail of bubble formation. While a systematic study of orifice size was not performed, in general, the idea was to keep the orifice size small consistent with obtaining a sufficient number of analyzable bubbles (typically 6 to 19 in approximately 3000 frames); the orifice sizes used were 0.3, 0.4, and 0.6 cm in diameters.

4.2 High-speed Cine Photography

Prior to each experimental run, the laboratory ventilation system was turned on; the bubbling tank was checked for leaks; and the inside compartment and objective lens of the camera were cleaned to ensure they were free of dust and foreign objects. The procedure before and during the photographing of bubbles growing at the orifice was then as follows:

(i) The bubbling tank was washed with ordinary soap and rinsed thoroughly with water. It was then dried with a

piece of clean cloth.

(ii) The two saturators were cleaned and filled to the two-third level with the experimental liquid.

(iii) The air supply system was connected to the bubbling unit and then turned on so that there was steady flow through the orifice. This precaution was necessary to prevent liquid leaking through the orifice while the tank was being filled.

(iv) The bubbling tank was filled with the experimental liquid to a depth of 12 cm above the orifice.

(v) The air flow rate was adjusted by means of the flow meter needle valve to obtain the desired value.

(vi) The camera was then focussed on the orifice plane with a piece of stainless wire placed in the centre of the orifice.

(vii) Two 650 watt lamps were turned on and the illumination was checked with the light meter for the correct combination of frame speed and aperture. The lamps were turned on only during the periods of the illumination check and photographing to prevent damage to the ground-glass screen from overheating.

(viii) The camera was loaded with film. The timing light was set at 100 pulses/sec and the aperture was adjusted according to the exposure-meter reading. A rod with known diameter was put in the plane of the orifice and photographed at 500 frames/sec for 2 sec.

(ix) With the rod removed, the air flow rate was rechecked to ensure the desired value and steady state

conditions. Values of indicated flow rate, line pressure downstream of the flow meter, and pool temperature were then recorded.

(x) The frame speed was set at 2000 frames/sec, the aperture readjusted, and the bubble images photographed.

For the experimental runs with liquid temperatures higher than room temperature, the liquid was preheated to approximately two degree Celsius above the desired temperature. The air was turned on. The heated liquid was then slowly poured into the bubbling tank surrounded by the water bath the temperature of which was being maintained by the immersion heater. During these experiments the saturators were in the water bath as well; the air to the orifice would then be at the same temperature as, and saturated with the vapor of, the pool liquid. Once equilibrium was established, the procedure in steps (v) to (x) was then repeated.

4.3 Calculation of Instantaneous Volume of A Bubble

The developed photographic films recording the sequence of the formation of each bubble were projected frame by frame on a screen to obtain a two-dimensional picture of the bubble. The screen, equipped with an X-Y digital reader, provided an easy way to measure bubble dimensions with an accuracy of approximately 0.01 cm in the actual bubble. The procedure for measuring and computing bubble volumes using the method of L'Ecuyer and Murthy[23] is illustrated in Appendix D.

By assuming the measured volume equal to a sphere of equal volume, the equivalent radius of the bubble, R_{eq} was obtained from the following equation:

$$R_{eq} = \left[\frac{3}{4\pi} \times V_{measured} \right]^{1/3} \quad 4.1$$

The subscript "eq" in R_{eq} is to be omitted later in the thesis while the implication of equivalent radius remains.

4.4 Experimental Conditions

The conditions under which the experiments were run are summarized in Table 4.1. Since the calibration results of the rotameter were in very good agreement with the manufacturer's calibration curve (see Appendix B), the manufacturer's curve was, therefore, used to obtain the indicated air flow rates corresponding to the rotameter scale readings recorded during the experiments. The indicated air flow rates were corrected to actual metering conditions according to the manufacturer's instructions; these flow rates in turn were then used to calculate the actual flow rate (air saturated with vapour at the pool temperature) at the orifice. The relevant calculations are presented in Appendix E. The values of the actual flow rates at the orifice were the ones used to determine the theoretical growth rate in a later section.

The liquids used in the present investigation were acetone, methanol, carbon tetrachloride, distilled water, and toluene. The first four liquids were supplied by Fisher Chemical Company and had a purity of 99.9 percent while the

Liquid	Orifice Dia. cm	Room Temp. °C	Liquid Temp. °C	Indicated Air Flow Rate cm ³ /sec	Actual Flow Rate at Orifice cm ³ /sec
Acetone	0.3	24.4	24.4	11.0	15.8
	0.3	24.4	24.4	24.0	34.8
Methanol	0.3	23.3	23.3	35.0	42.3
	0.4	25.6	25.6	44.4	56.3
Carbon Tetra- chloride	0.3	23.3	31.1	16.5	21.1
	0.3	23.3	31.1	29.3	37.9
Distilled Water	0.6	25.5	25.5	88.7	113.5
	0.6	23.2	50.0	111.5	180.1
Toluene	0.6	23.3	35.6	91.9	130.1

Table 4.1 Experimental Conditions For the Bubble Growth Experiments.

distilled water was readily available from the laboratory still. The liquid properties of the above liquids are presented in Appendix C.

The liquid temperatures were controlled within approximately one degree Celsius of the saturation temperatures corresponding to the pressures used by Cole and Shulman[6].

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Bubble Behavior

There were three types of bubble formation observed in the films and they could be classified as follows:

- (a) Double bubbles,
- (b) Series of three bubbles,
- (c) Series of more than three bubbles.

The typical behavior of double-bubble formation is shown in Fig. 5.1. The first bubble (sometimes referred as the "leading bubble") started with a small meniscus at the orifice. This small meniscus increased its size due to the mass flow into the bubble and generally became somewhat pear-shaped for the smaller orifices but more spherical for the largest orifice. As the size of the first bubble increased further, a stage was reached when the upward forces acting upon the bubble had increased sufficiently to start lifting the bubble off the orifice. A very short stem started forming and connected the first bubble to the orifice. As the first bubble travelled up further, the stem either was broken clear or ended in a sharp neck. The lower part of the stem at the orifice formed the second bubble (sometimes referred as the "secondary bubble") which always caught up to the first bubble straight away. As the second

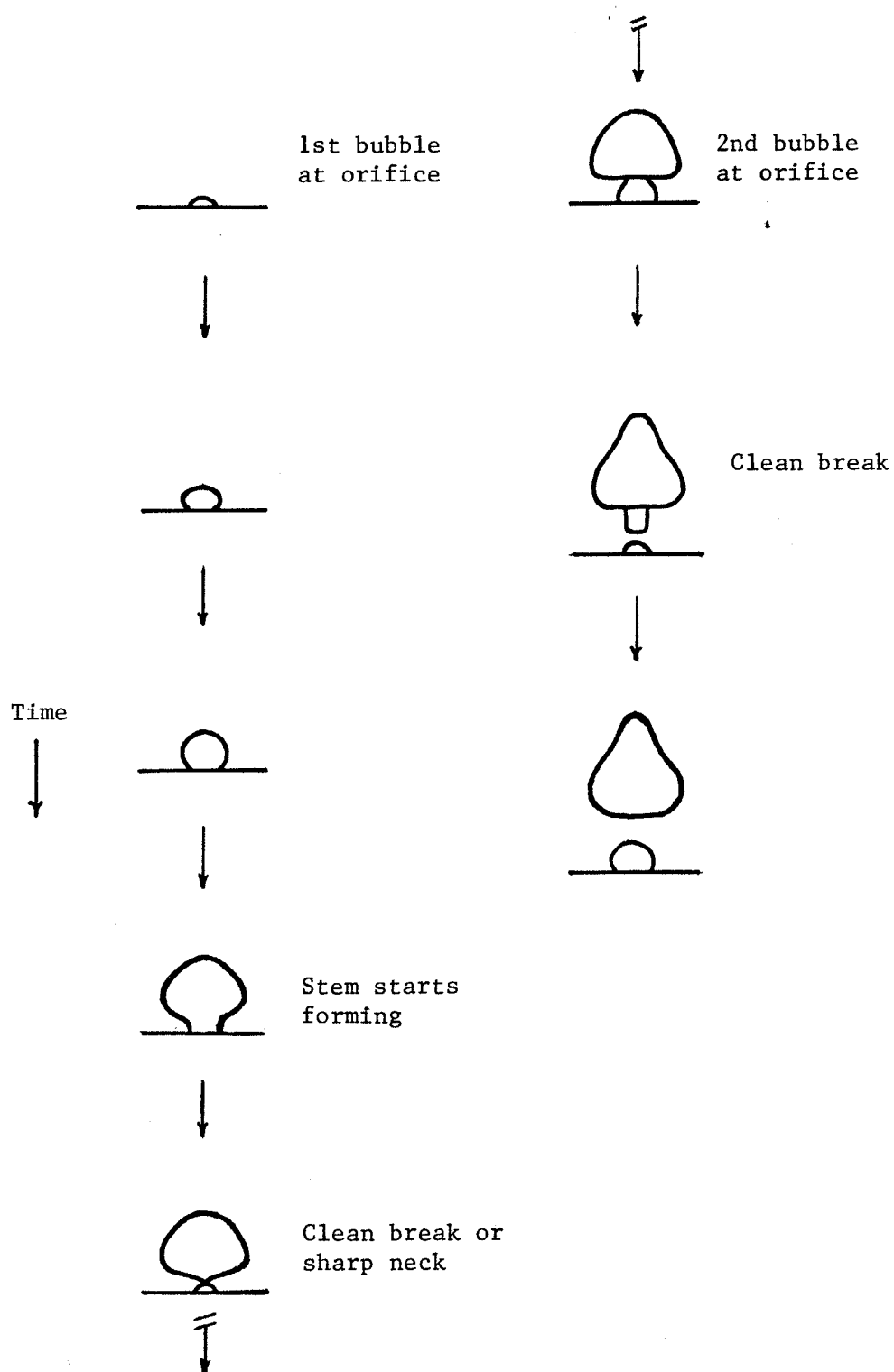


Fig. 5.1 Typical Behavior of Double Bubbles.

bubble continued to grow, it protruded into the first bubble, subsequently causing deformation of the top of the first bubble. The size of the second bubble was smaller than that of the first bubble and ended in a stem and clean break. After the second bubble had detached from the orifice, it combined with the first bubble and travelled up in the liquid column as a single unit.

Figure 5.2 shows the typical behavior of a three-bubble series in which the first and second bubbles of the series behaved the same as those of the double bubbles described above. The third bubble in the series started completely free after the second bubble broke free at the orifice. As the third bubble grew at the orifice, it caught up to the combination of the first and second bubbles. During the later part of growth period, the third bubble fed the preceding bubble (combination of first and second bubbles) causing it to enlarge in size. The third bubble usually ended in a stem and clean break or sharp neck giving finally for the three bubbles a shape like that of a mushroom. In a few cases, mainly in toluene, the first bubble, for a small portion of its growth, overlapped the bottom of the previous bubble, but with its outline clearly visible such that its volume could be calculated; in this case such a bubble was still considered as a first bubble.

For series of more than three bubbles, the behavior of the first and second bubbles in the series was very similar to that of double bubbles. In fact, the bubble series of

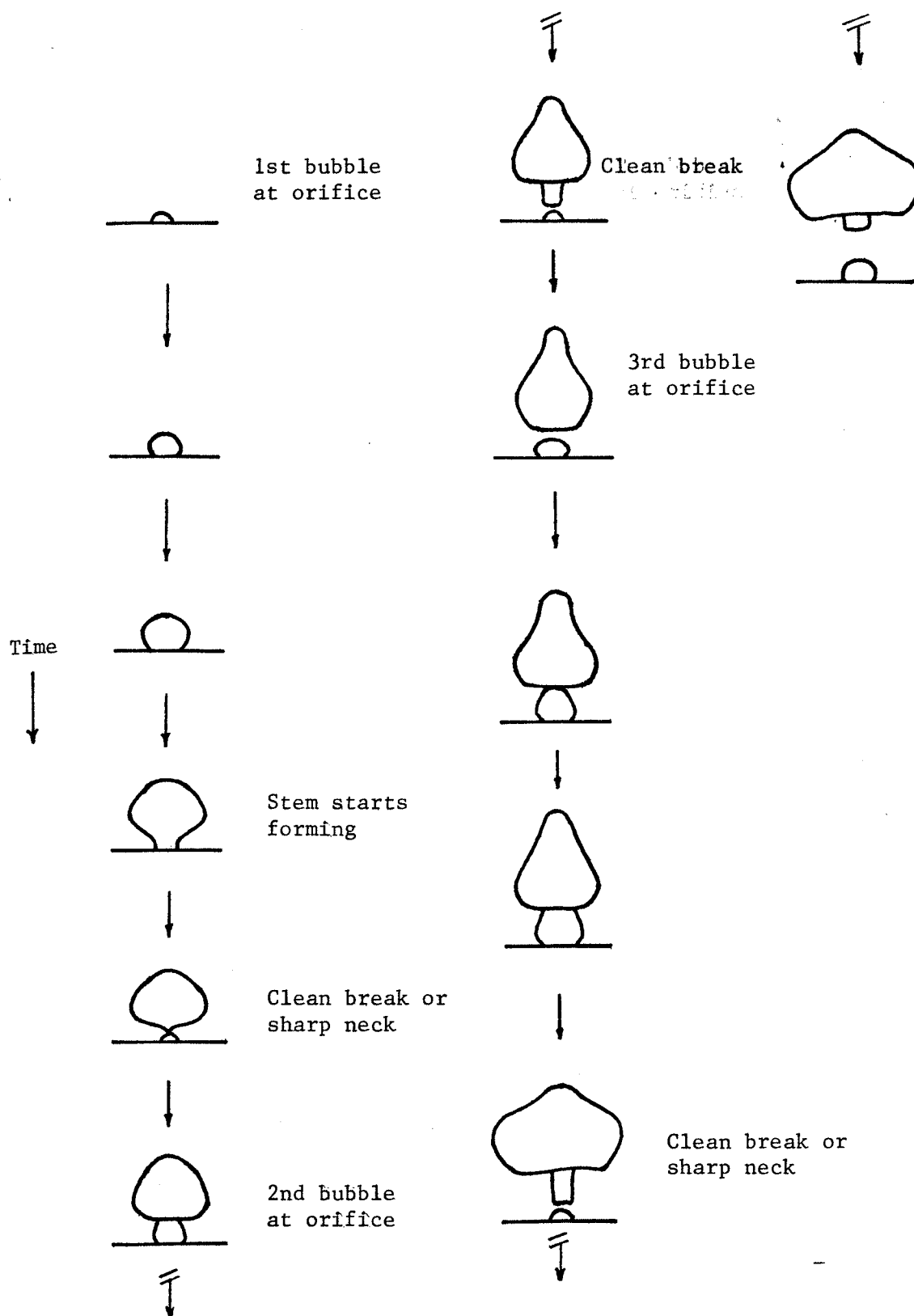


Fig. 5.2 Typical Behavior of Three-bubble Series.

this type could be broken down into: a number of double bubbles, a number of three-bubble series, or some combination of double bubbles and three-bubble series. The bubble connecting these double bubbles and/or three-bubble series together was a "first-like" bubble which generally acted like a first bubble, except this "first-like" bubble, while at the orifice, contacted the previous bubble for part of its growth period during which its volume could not be measured. A "first-like" bubble was followed by a typical second bubble.

Table 5.1 gives the summary of the bubble types for different liquids and conditions. It was always first bubbles which were analyzed in terms of bubble volume against time.

5.2 Bubble Growth and Departure Size

5.2.1 Presentation of results

Figures 5.3 through 5.11 show plots of bubble equivalent radius against time for all liquids (the subscript "eq" in R_{eq} is dropped in the figures). The tabulated bubble growth data and bubble identification are given in Appendix F. The bubble departure time, t_d , and bubble departure radius, R_d , are presented in Table 5.2.

As mentioned earlier, the bubble growth results reported here are for "first bubbles", as described in the Previous section. The zero time for bubbles was taken

Film No.	Liquid and Conditions	Frame Nos. Analyzed	Bubble Type Observed
3A11	Acetone; Orifice Dia., 0.3 cm; Actual Flow Rate, 15.8 cm ³ /sec; Liquid Temp., 24.4 °C.	0 - 3000	15 Double Bubbles; 4 5-Bubble Series.
3A24	Acetone; Orifice Dia., 0.3 cm; Actual Flow Rate, 34.8 cm ³ /sec; Liquid Temp., 24.4 °C.	29 - 3072	5 Double Bubbles; 1 4-Bubble Series; 3 5-Bubble Series; 2 6-Bubble Series; 1 12-Bubble Series.
3M35	Methanol; Orifice Dia., 0.3 cm; Actual Flow Rate, 42.3 cm ³ /sec; Liquid Temp., 23.3 °C.	84 - 2854	7 Double Bubbles; 1 4-Bubble Series; 1 6-Bubble Series; 1 11-Bubble Series; 1 12-Bubble Series.
4M44.4	Methanol; Orifice Dia., 0.4 cm; Actual Flow Rate, 56.3 cm ³ /sec; Liquid Temp., 25.6 °C.	16 - 3540	1 Double Bubble; 1 4-Bubble Series; 1 7-Bubble Series; 1 8-Bubble Series; 1 18-Bubble Series; 1 14-Bubble Series.
3C16.5	Carbon Tetrachloride; Orifice Dia., 0.3 cm; Actual Flow Rate, 21.1 cm ³ /sec; Liquid Temp., 31.1 °C.	16 - 2834	13 Double Bubbles; 1 3-Bubble Series; 1 5-Bubble Series; 1 6-Bubble Series; 1 9-Bubble Series.

Continued on next page.

Table 5.1 Summary of Bubble Type Observed in Different Liquids and Conditions.

Film No.	Liquid and Conditions	Frame Nos. Analyzed	Bubble Type Observed
3C29.3	Carbon Tetrachloride; Orifice Dia., 0.3 cm; Actual Flow Rate, 37.9 cm ³ /sec; Liquid Temp., 31.1°C.	12 - 3011	8 Double Bubbles; 1 5-Bubble Series; 1 6-Bubble Series; 2 7-Bubble Series;
6W88.7	Distilled Water; Orifice Dia., 0.6 cm; Actual Flow Rate, 113.5 cm ³ /sec; Liquid Temp., 25.5°C.	2 - 2995	1 Double Bubble; 5 3-Bubble Series; 2 4-Bubble Series; 2 5-Bubble Series.
6W111.5	Distilled Water; Orifice Dia., 0.6 cm; Actual Flow Rate, 180.1 cm ³ /sec; Liquid Temp., 50.0°C.	49 - 2918	6 Double Bubbles; 5 3-Bubble Series; 1 4-Bubble Series; 1 5-Bubble Series.
6T91.9	Toluene; Orifice Dia., 0.6 cm; Actual Flow Rate, 130.1 cm ³ /sec; Liquid Temp., 35.6°C.	56 - 3166	6 3-Bubble Series; 1 4-Bubble Series; 3 6-Bubble Series.

Table 5.1 - (Cont.) Summary of Bubble Type Observed in Different Liquids and Conditions.

Acetone

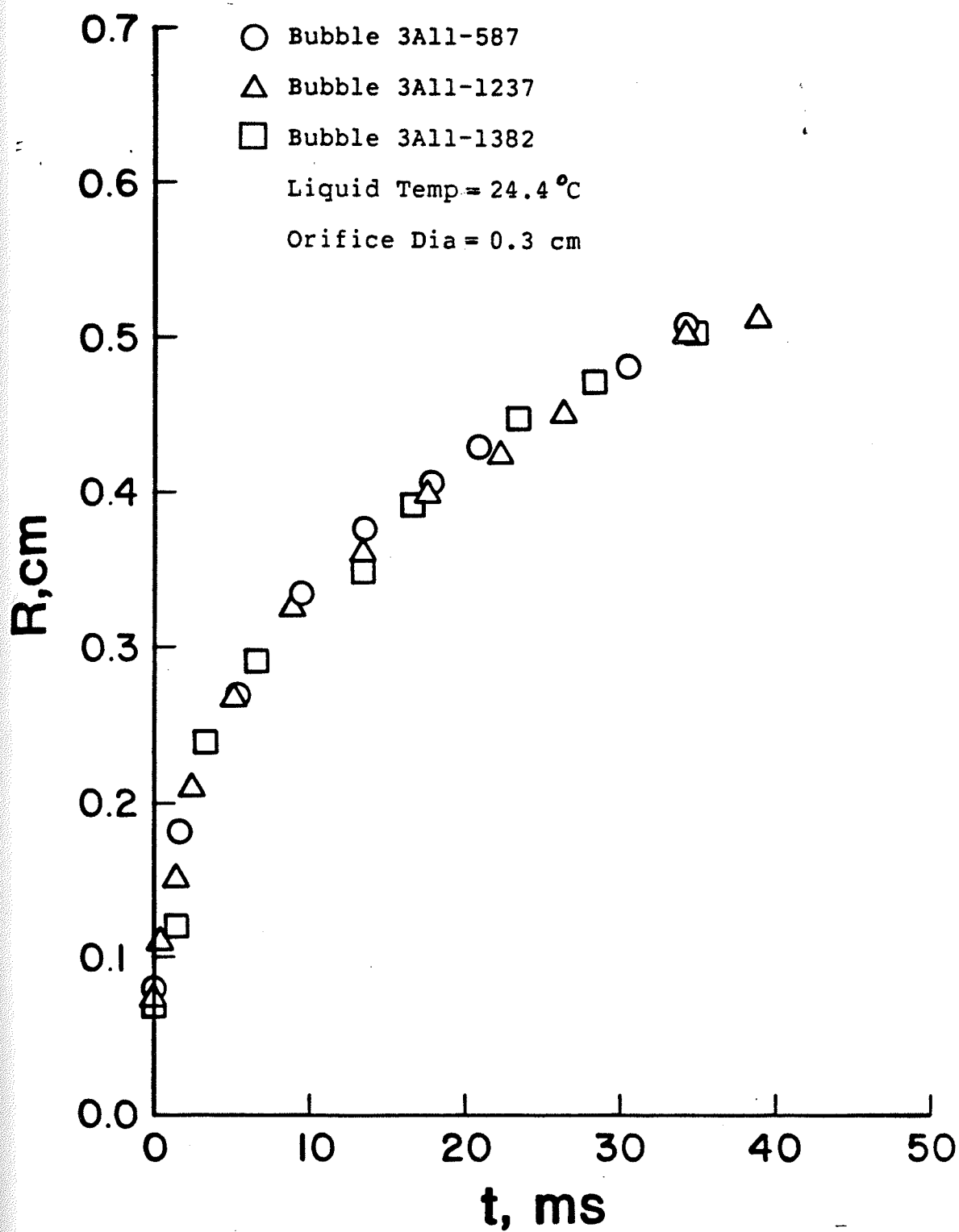


Fig. 5.3 Bubble Growth Data in Acetone.
(Actual Flow Rate at Orifice, 15.8 cm³/sec).

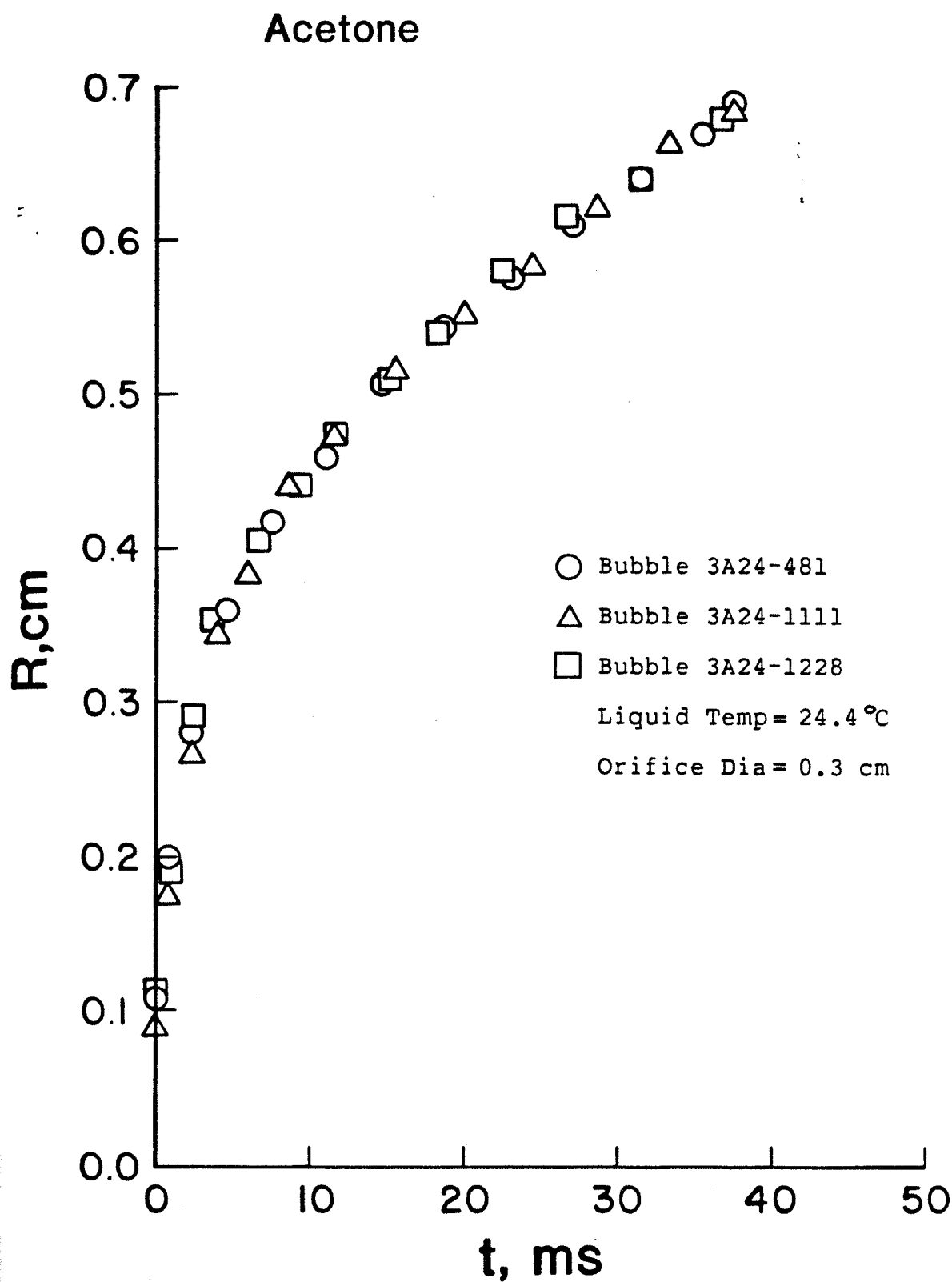


Fig. 5.4 Bubble Growth Data in Acetone.
(Actual Flow Rate at Orifice, 34.8 cm³/sec.)

Methanol

○ Bubble 3M35-800

△ Bubble 3M35-1749

□ Bubble 3M35-2640

Liquid Temp = 23.3 °C

Orifice Dia = 0.3 cm

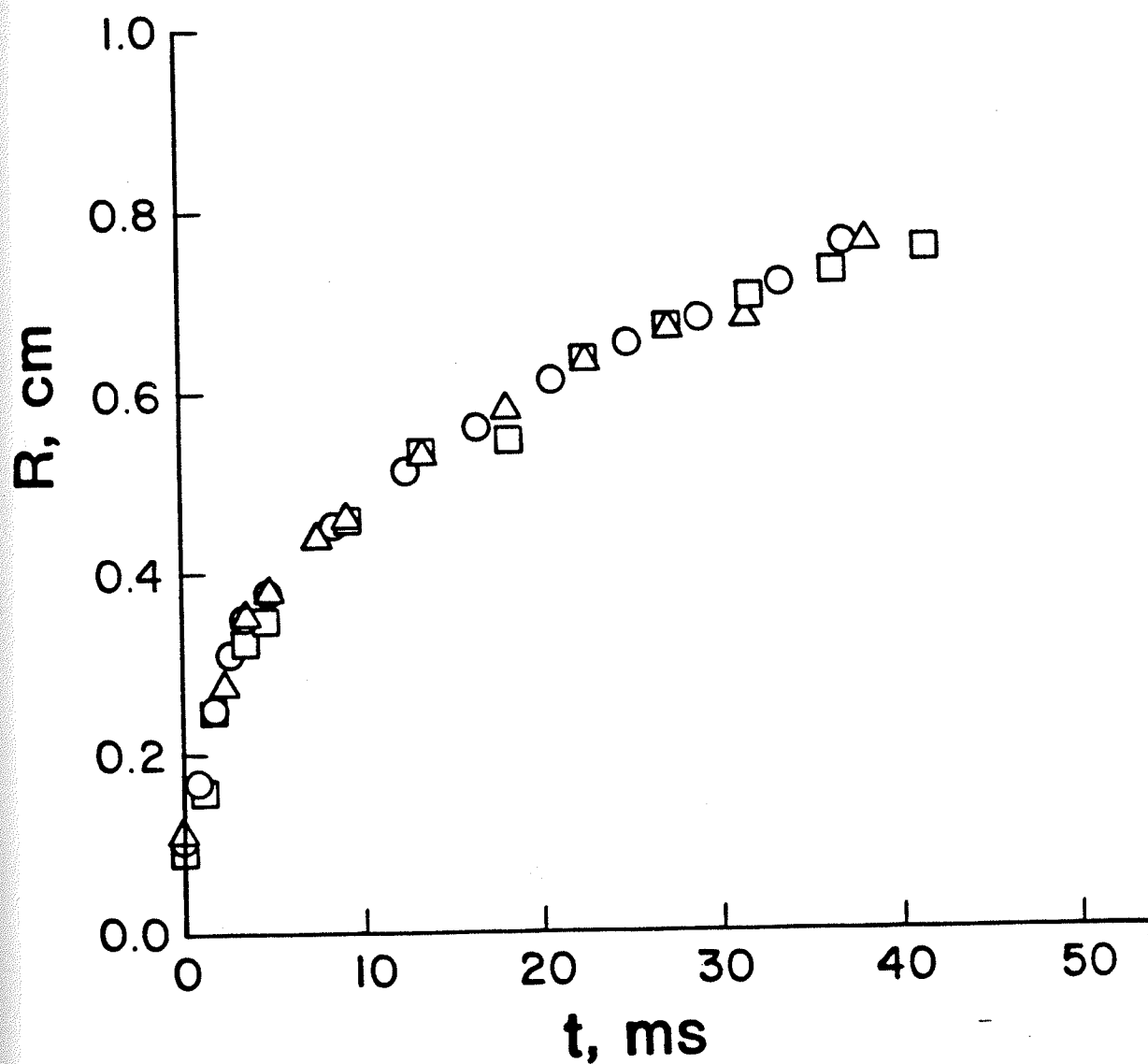


Fig. 5.5 Bubble Growth Data in Methanol.
(Actual Flow Rate at Orifice, 42.3 cm³/sec.)

Methanol

○ Bubble 4M44.4-452

△ Bubble 4M44.4-1004

□ Bubble 4M44.4-2652

Liquid Temp = 25.6°C

Orifice Dia = 0.4 cm

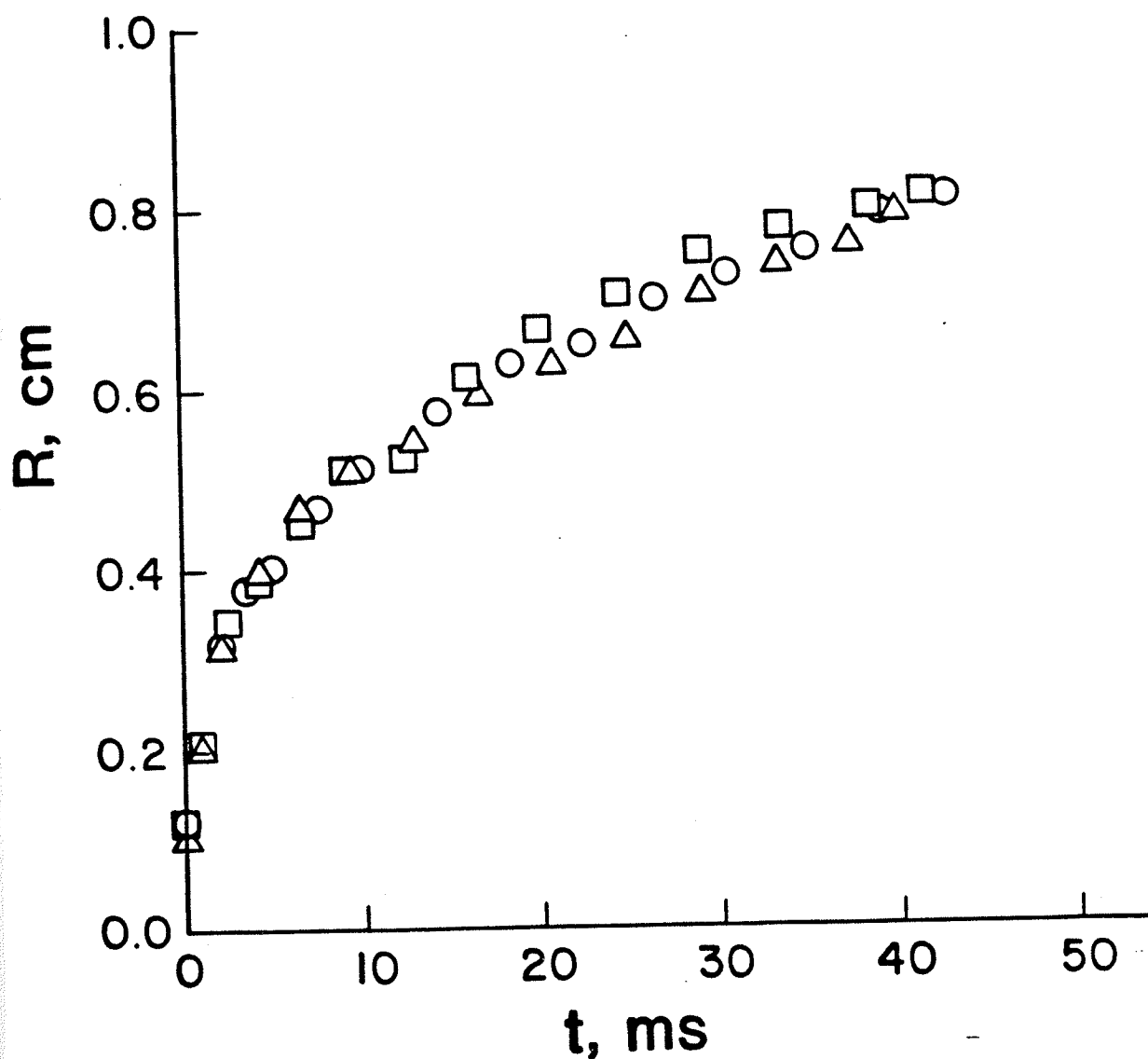


Fig. 5.6 Bubble Growth Data in Methanol.
(Actual Flow Rate at Orifice, 56.3 cm³/sec.)

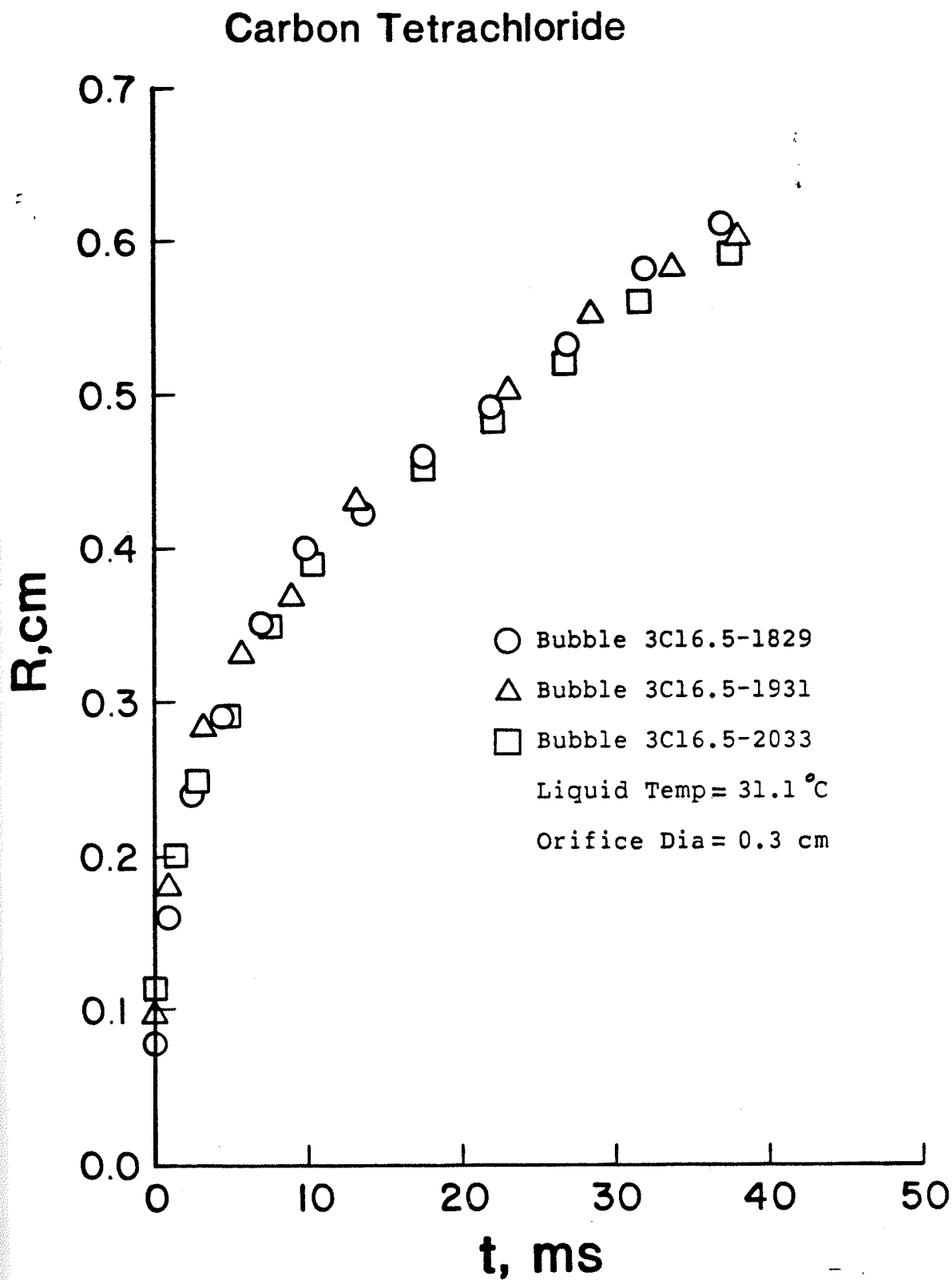


Fig. 5.7 Bubble Growth Data in Carbon Tetrachloride.
(Actual Flow Rate at Orifice, 21.1 cm³/sec.)

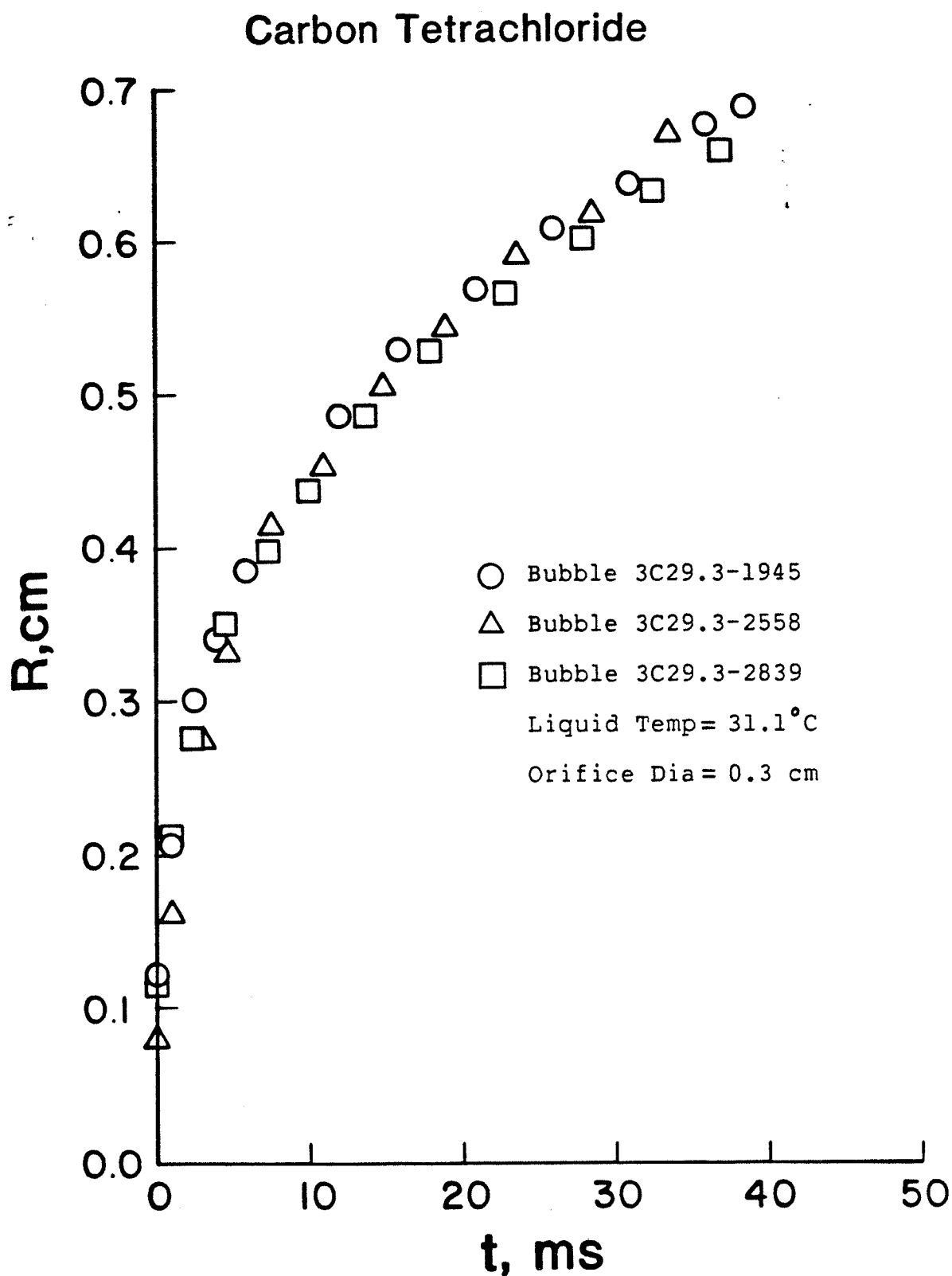


Fig. 5.8 Bubble Growth Data in Carbon Tetrachloride.
(Actual Flow Rate at Orifice, $37.9 \text{ cm}^3/\text{sec}$).

Distilled Water

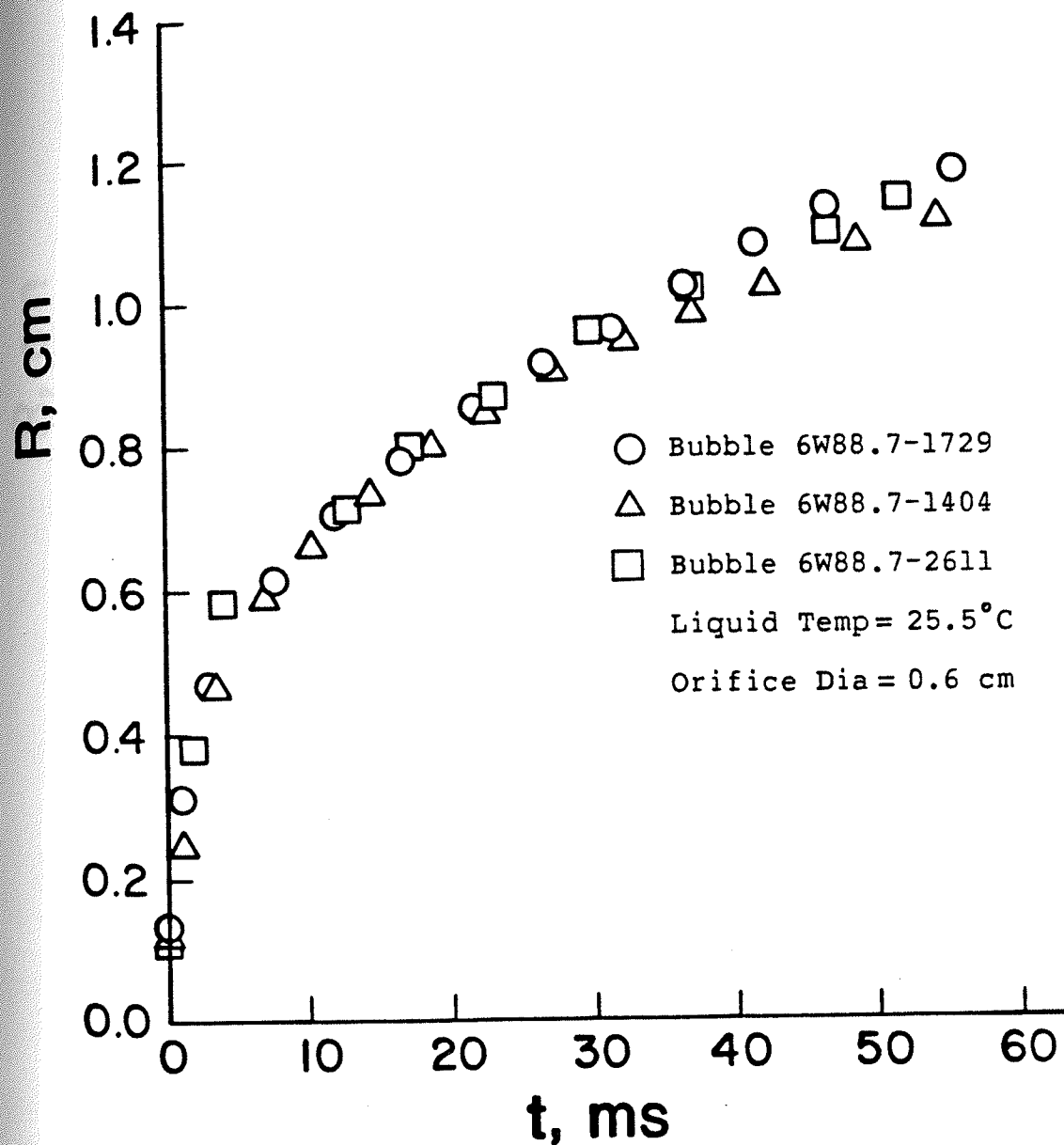


Fig. 5.9 Bubble Growth Data in Distilled Water.
(Actual Flow Rate at Orifice, 113.5 cm³/sec).

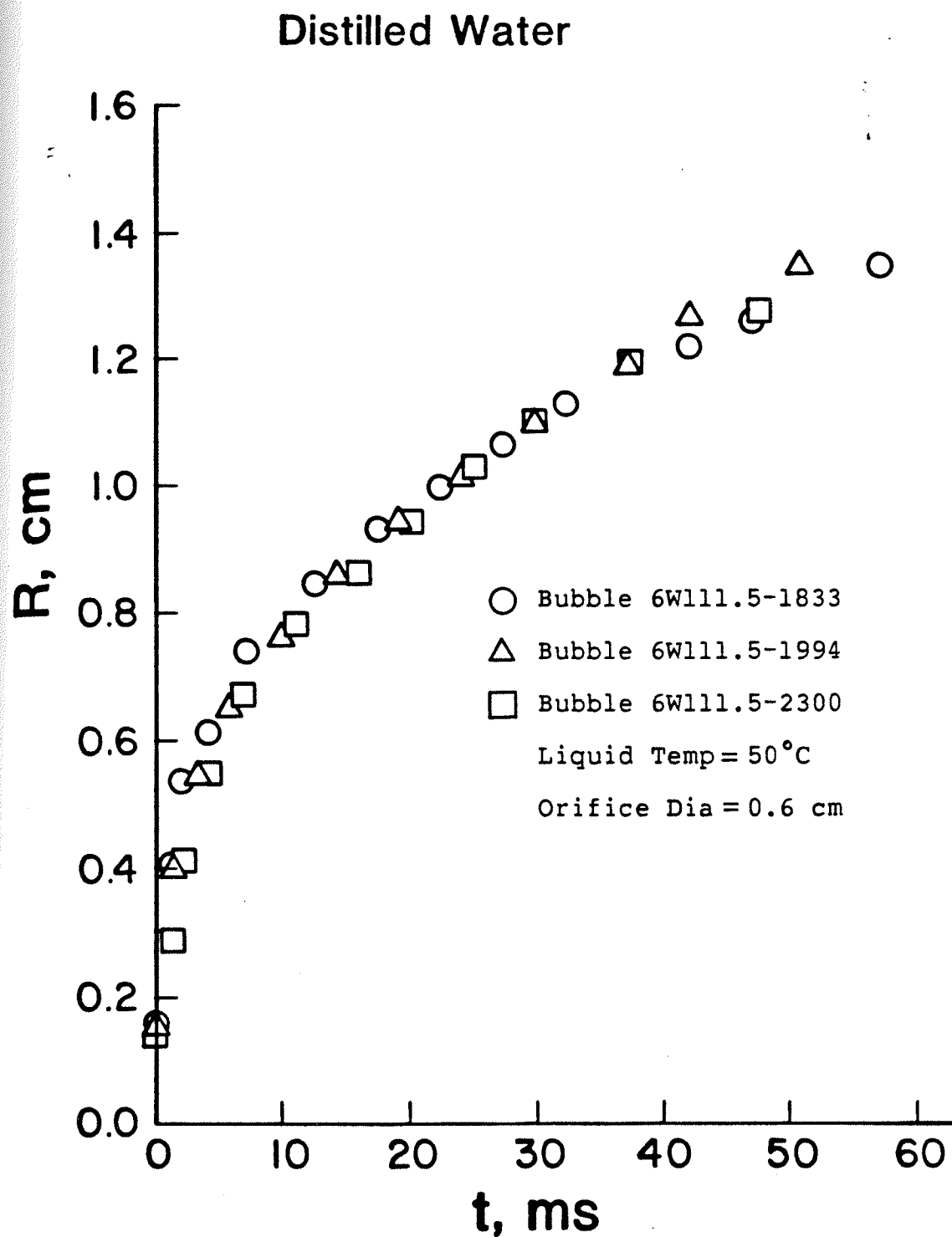


Fig. 5.10 Bubble Growth Data in Distilled Water.
(Actual Flow Rate at Orifice, 180.1 cm³/sec).

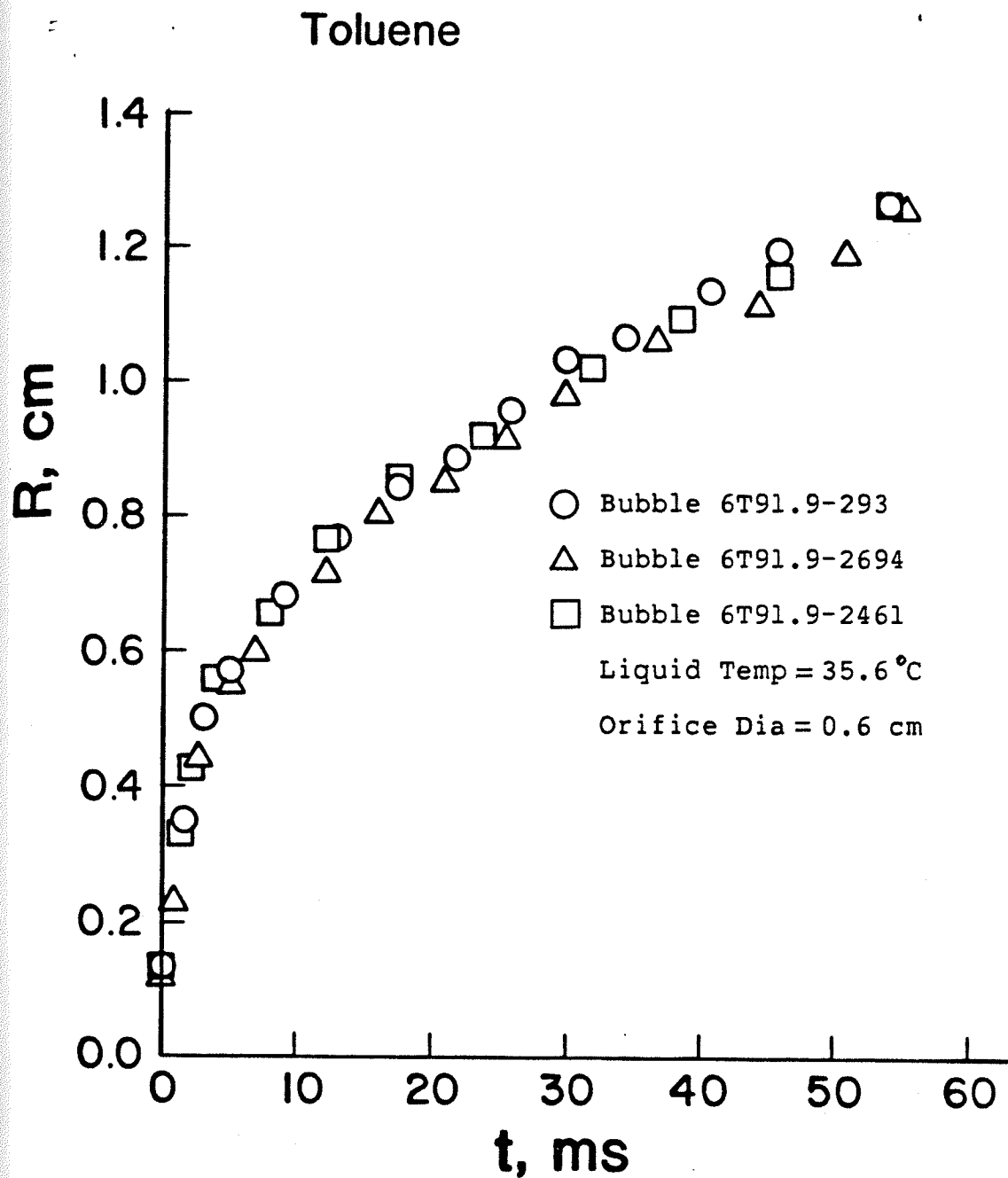


Fig. 5.11 Bubble Growth Data in Toluene.
(Actual Flow Rate at Orifice, 130.1 cm³/sec).

Liquid	Bubble Identification	Orifice Dia. cm	Actual Flow rate cm ³ /sec	Bubble Departure Time, t_d ms	Bubble Departure Radius, R_d cm
Acetone	3A11-597 3A11-1237 3A11-1382	0.3	15.8	34.2 39.1 35.0	0.507 0.510 0.503 (Ave.:0.507)
	3A24-481 3A24-1111 3A24-1228	0.3	34.8	37.5 37.4 36.8	0.689 0.684 0.680 (Ave.:0.684)
Methanol	3M35-800 3M35-1749 3M35-2640	0.3	42.3	37.9 38.2 41.4	0.759 0.760 0.747 (Ave.:0.755)
	4M44.4-452 4M44.4-1004 4M44.4-2652	0.4	56.3	42.9 40.0 41.4	0.807 0.788 0.810 (Ave.:0.802)
Carbon Tetra-chloride	3C16.5-1829 3C16.5-1931 3C16.5-2033	0.3	21.1	37.0 37.9 37.3	0.610 0.600 0.590 (Ave.:0.600)
	3C29.3-1945 3C29.3-2558 3C29.3-2839	0.3	37.9	38.5 33.3 37.1	0.687 0.670 0.657 (Ave.:0.671)
Distilled Water	6W88.7-1404 6W88.7-1729 6W88.7-2611	0.6	113.5	55.5 56.0 51.9	1.130 1.188 1.174 (Ave.:1.164)
	6W111.5-1833 6W111.5-1994 6W111.5-2300	0.6	180.1	57.0 51.2 48.1	1.351 1.352 1.283 (Ave.:1.329)
Toluene	6T91.9-293 6T91.9-2461 6T91.9-2694	0.6	130.1	54.9 54.4 55.8	1.248 1.266 1.265 (Ave.:1.260)

Table 5.2 Bubble Departure Times and Radii

corresponding to the frame when the first bubble appeared as a meniscus which was left behind at the orifice by the preceding bubble and had a finite radius. For the three bubbles reported for toluene, each bubble was in contact with the preceding bubble for typically four frames (of a bubble life of approximately 130 frames) during which time it was still possible to calculate the bubble volume as the outline was still clear in the small overlap area. The bubble departure time, t_d , and departure radius, R_d , were taken corresponding to the frame when it showed a clean break or sharp neck between the first and the second bubbles.

For each experimental condition (liquid temperature, orifice diameter, and air flow rate), three sets of bubble growth data were analyzed in order to check if they were similar. It is seen from Figs. 5.3 to 5.11 that the bubble growth results for the three bubbles analysed in each case fall close to one another for the same conditions. Repeatability tests were performed on methanol and distilled water and the results are presented in Appendix A. The bubble growth results of the repeatability tests for both liquids are in good agreement with those of the original experiments (see Appendix A for quantitative discussion).

5.2.2 Comparison of experimental and theoretical bubble growth

Figures 5.12 through 5.20 show experimental growth

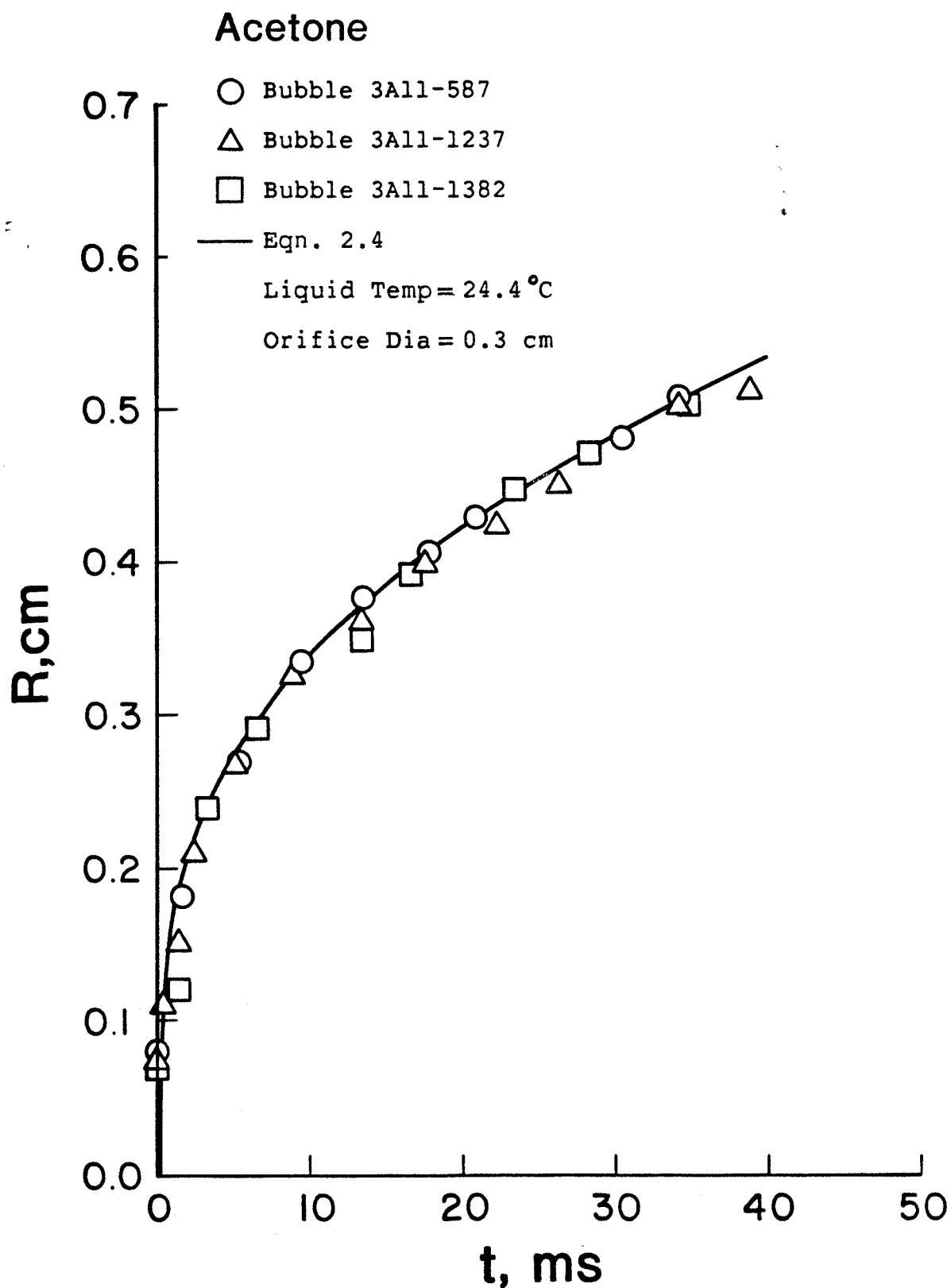


Fig. 5.12 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Acetone - Actual Flow Rate, 15.8 cm³/sec.

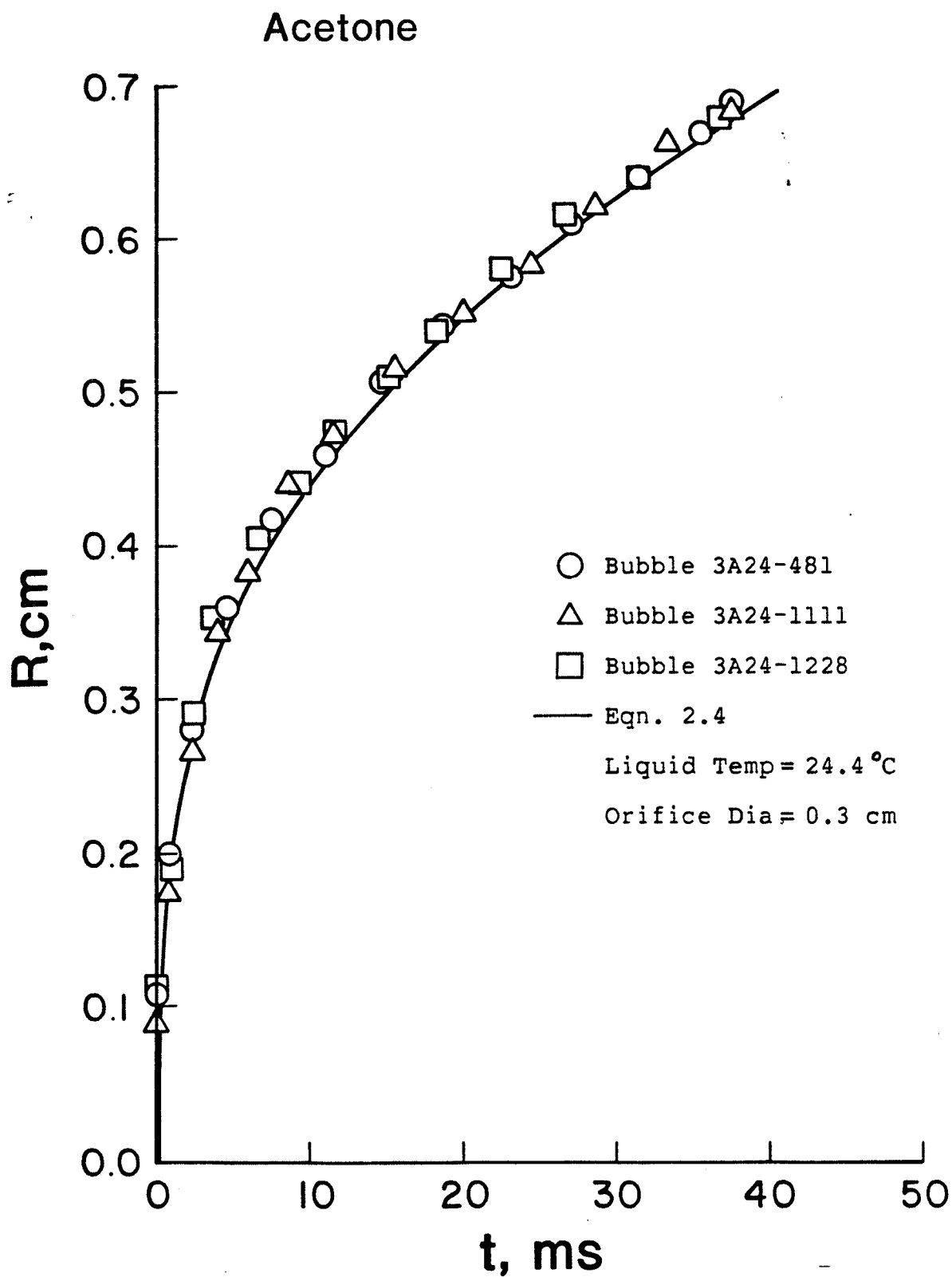


Fig. 5.13 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Acetone - Actual Flow Rate, $34.8 \text{ cm}^3/\text{sec}$.

Methanol

○ Bubble 3M35-800

△ Bubble 3M35-1749

□ Bubble 3M35-2640

— Eqn. 2.4

Liquid Temp = 23.3 °C

Orifice Dia = 0.3 cm

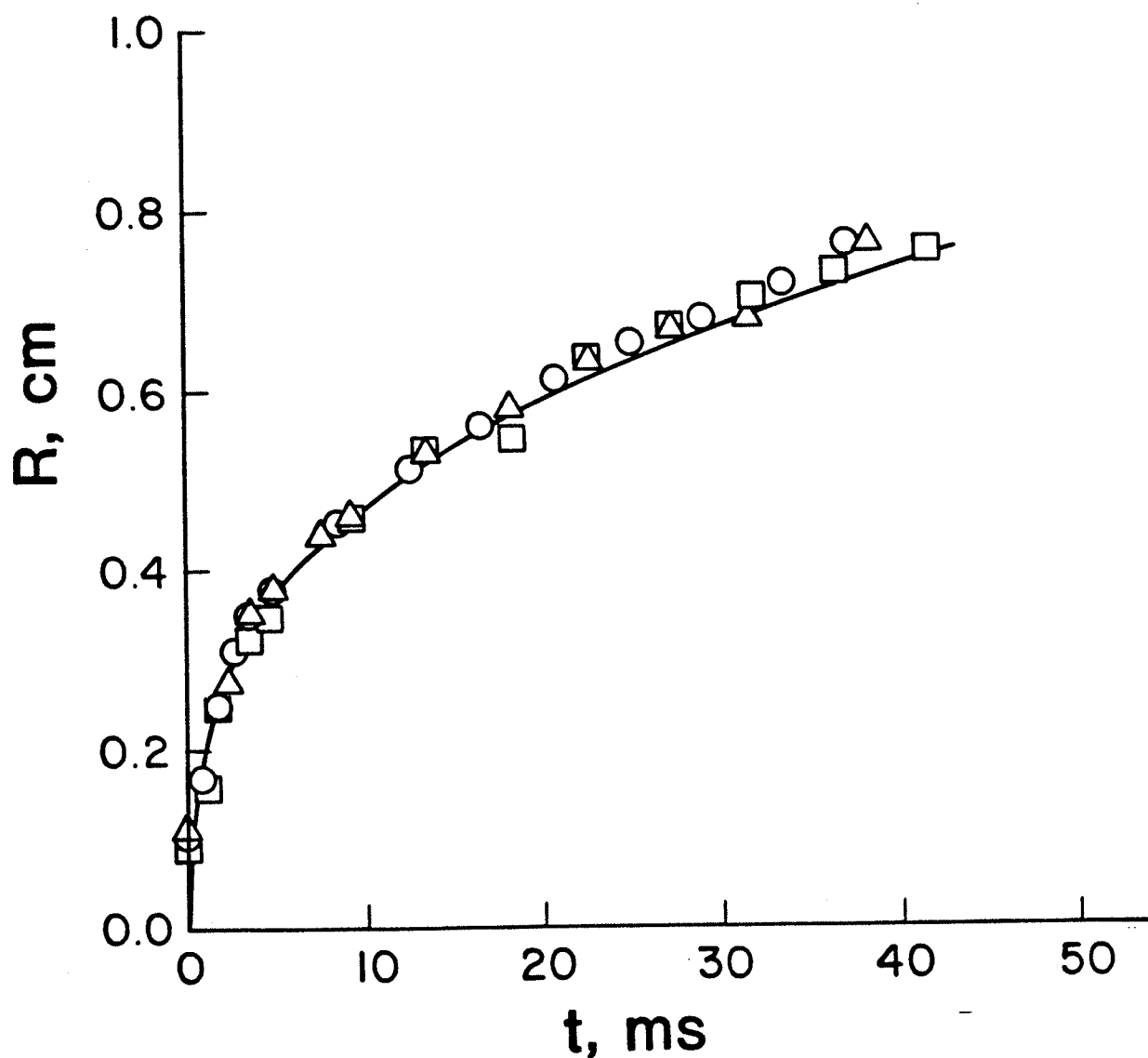


Fig. 5.14 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Methanol - Actual Flow Rate, 42.3 cm³/sec.

Methanol

- Bubble 4M44.4-452
- △ Bubble 4M44.4-1004
- Bubble 4M44.4-2652
- Eqn. 2.4

Liquid Temp = 25.6°C

Orifice Dia = 0.4 cm

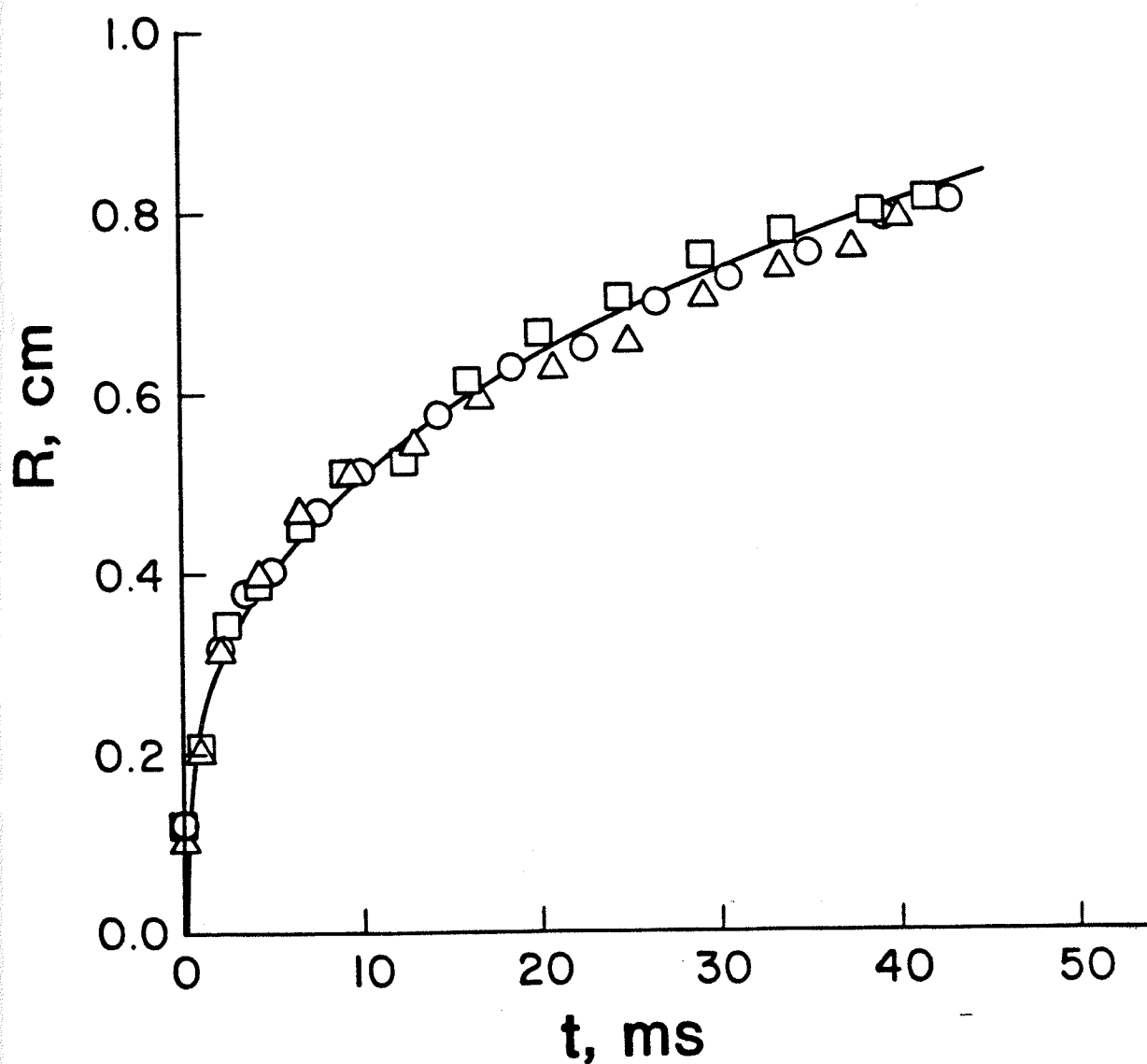


Fig. 5.15 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Methanol - Actual Flow Rate, 56.3 cm³/sec.

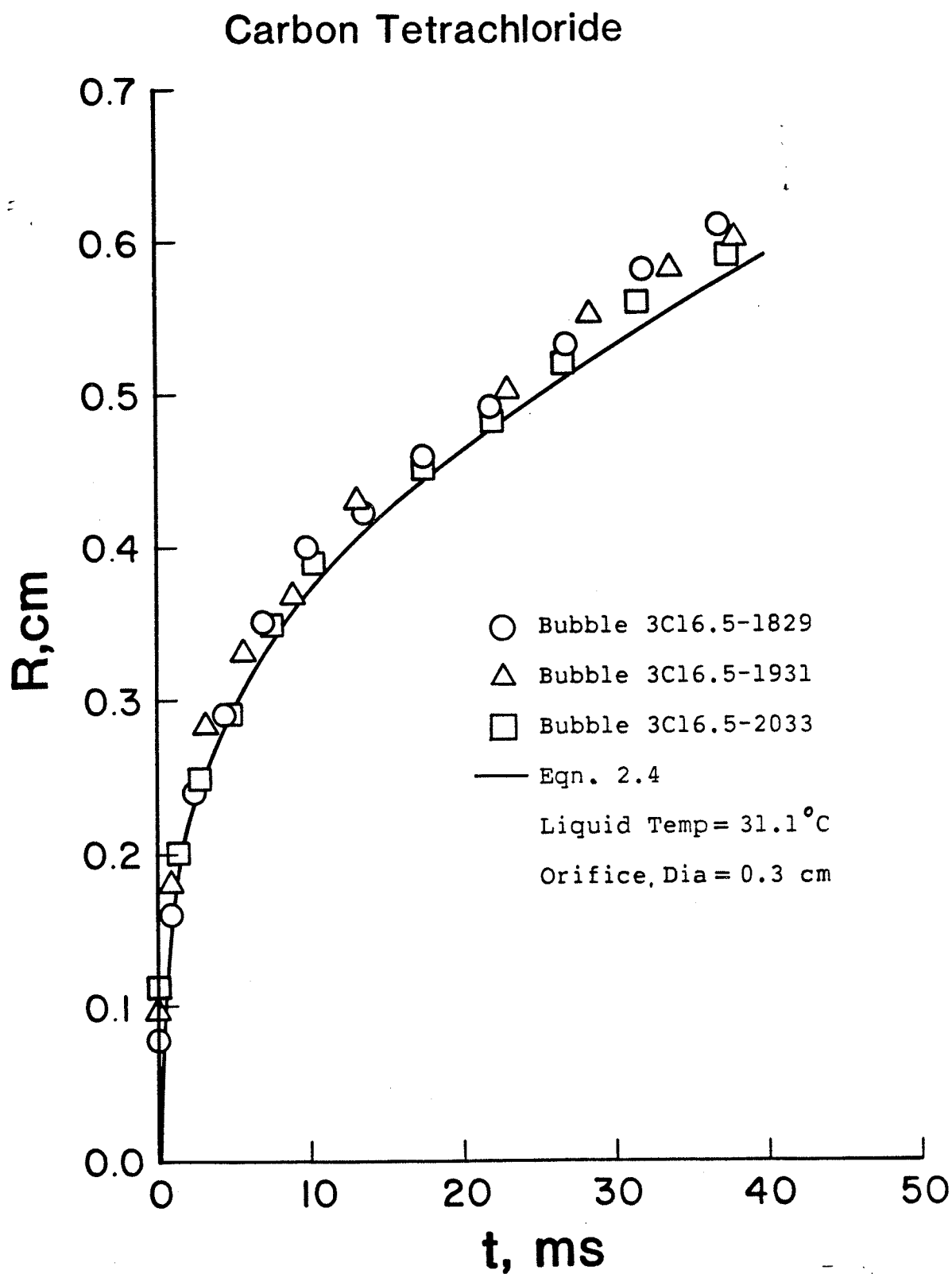


Fig. 5.16 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Carbon Tetrachloride - Actual Flow Rate, 21.1 cm³/sec.

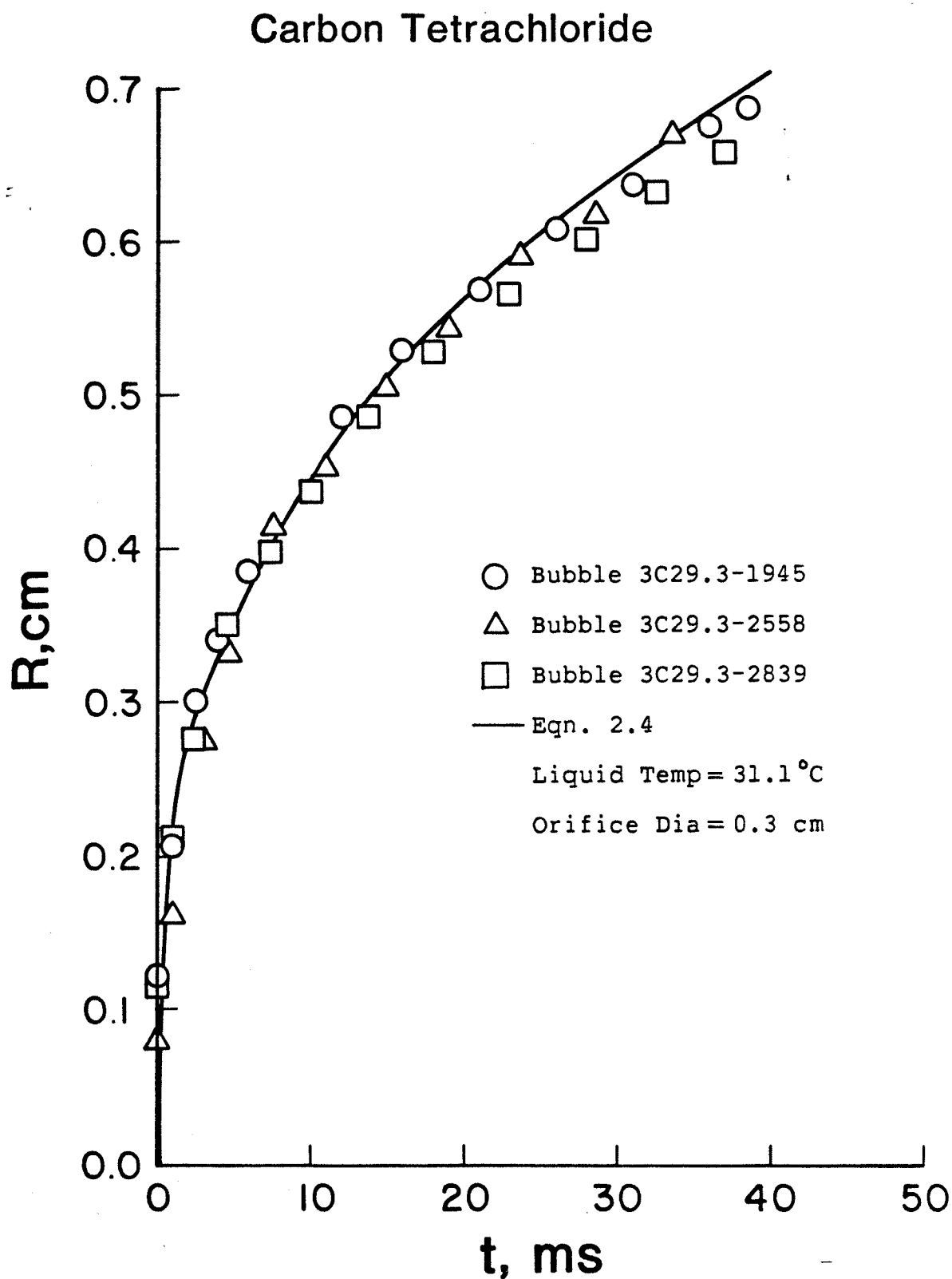


Fig. 5.17 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Carbon Tetrachloride - Actual Flow Rate, 37.9 cm³/sec.

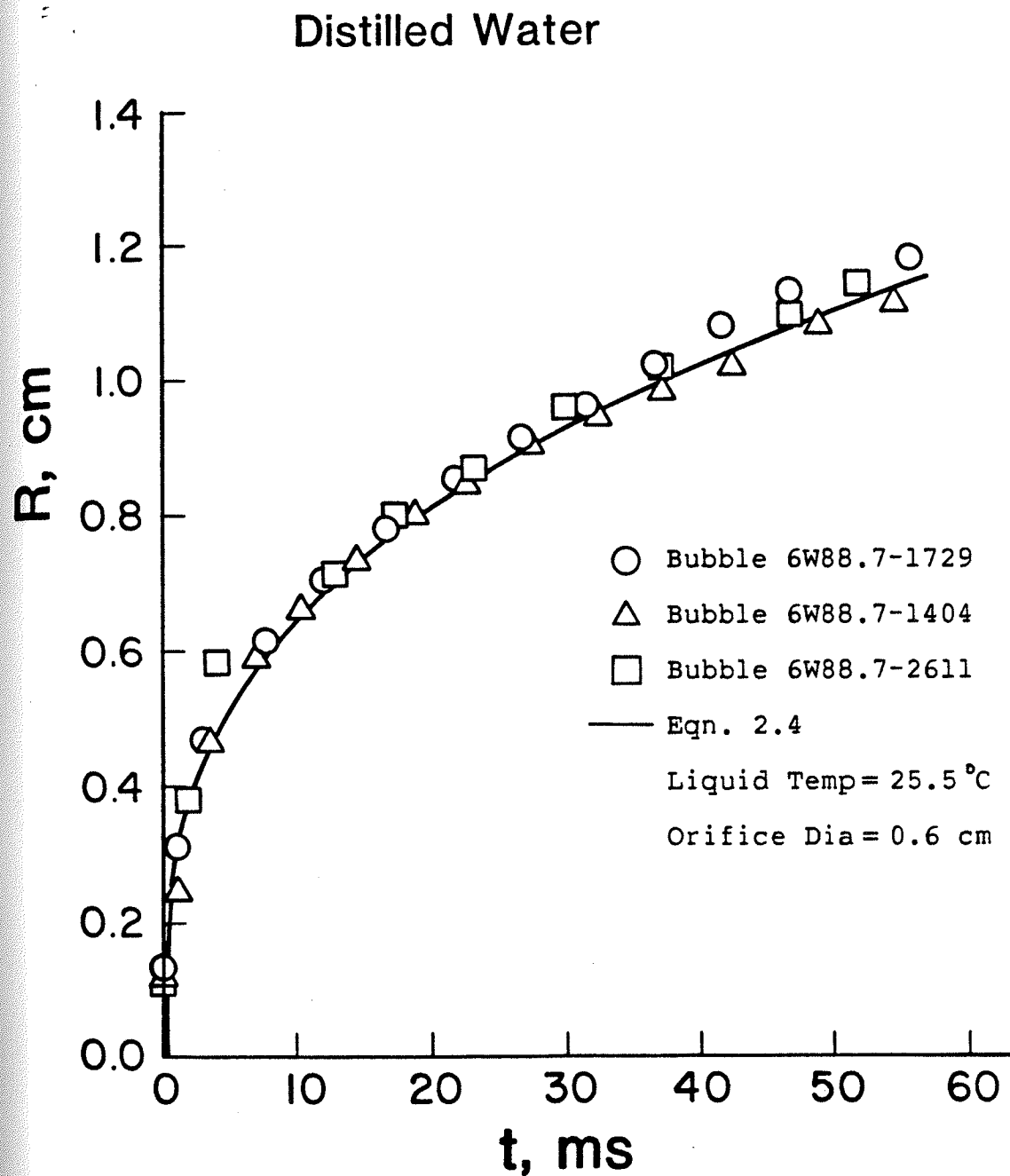


Fig. 5.18 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Distilled Water - Actual Flow Rate, 113.5 cm³/sec.

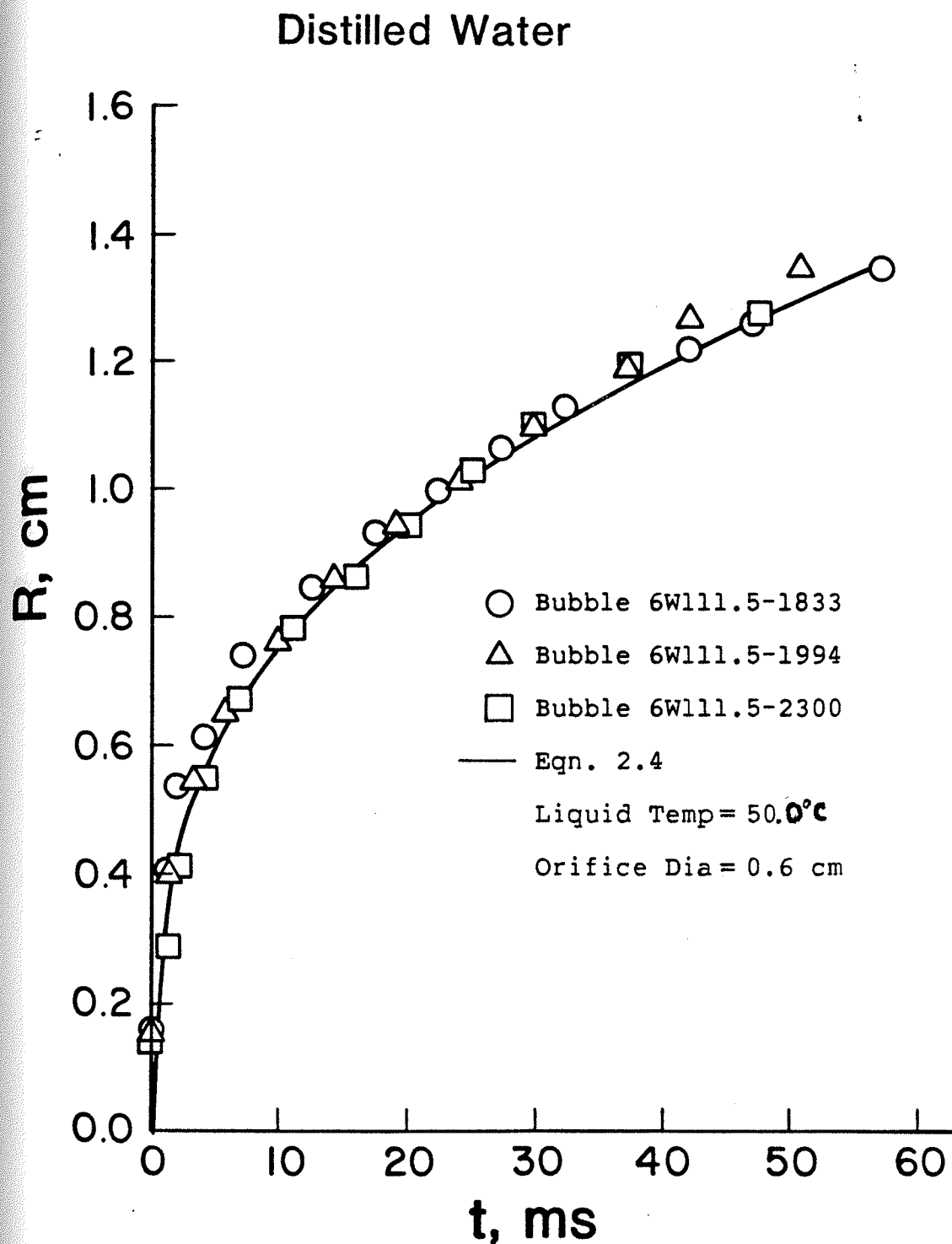


Fig. 5.19 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Distilled Water - Actual Flow Rate, 180.1 cm³/sec.

Toluene

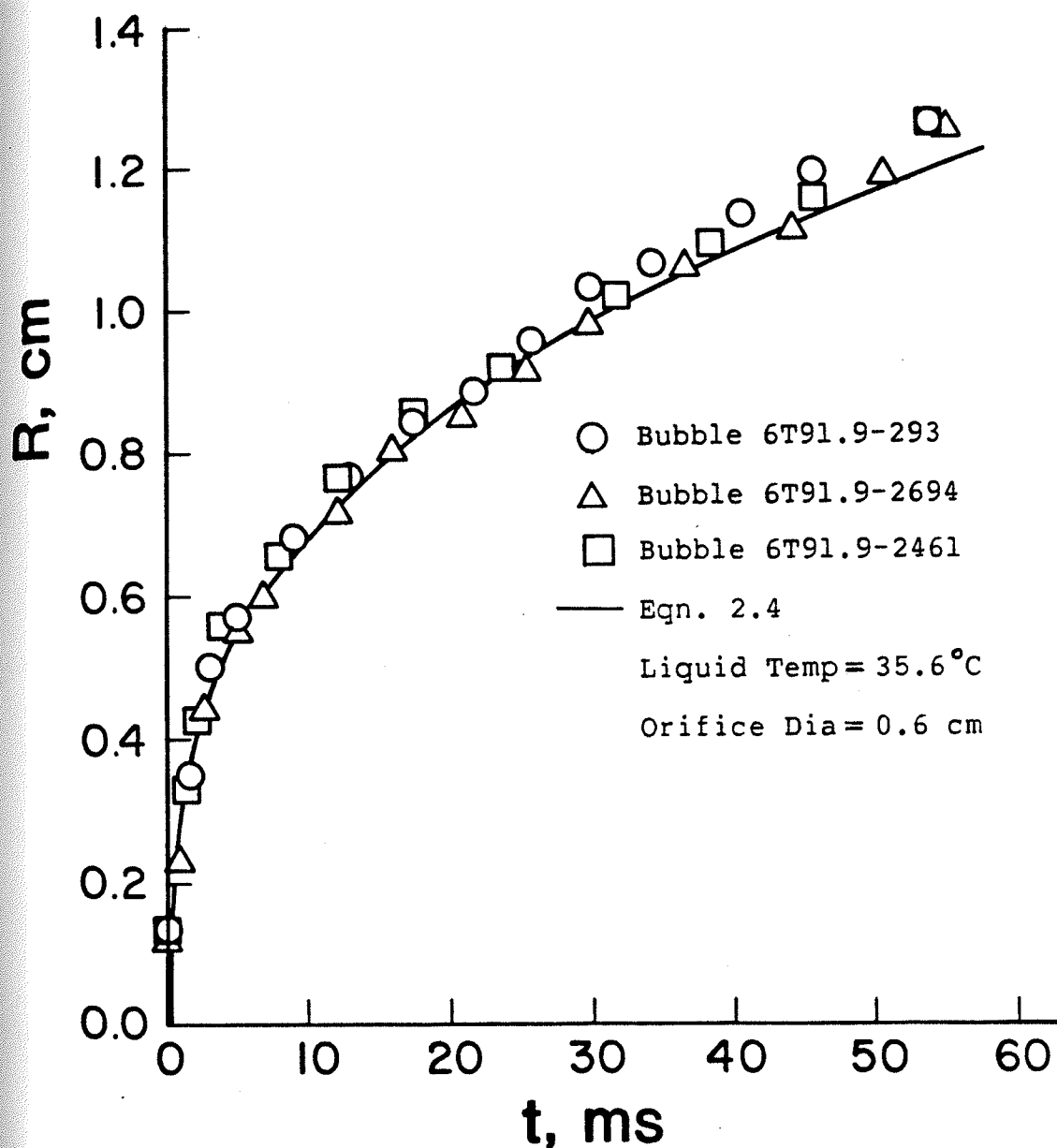


Fig. 5.20 Comparison of Experimental Results and Bubble Growth Eqn. 2.4 for Toluene - Actual Flow Rate, $130.1 \text{ cm}^3/\text{sec}$.

results obtained in the present work, along with the corresponding theoretical curves from Eqn. 2.4, i.e. $R = (3Q/4\pi)^{1/3} t^{1/3}$. It can be seen that the experimental results are in excellent agreement with the theoretical curves for the entire period of growth in all liquids except at zero time when the experimental results have a finite radius. However, it can be concluded that the present apparatus genuinely operated under constant-flow conditions.

5.2.3 Comparison of experimental and theoretical bubble departure size

Table 5.3 gives the present experimental departure radii for all test liquids as well as the departure radii predicted by the theory of Kumar and Kuloor[22]. The experimental value for each air flow rate is the average of the three bubbles analyzed for the same conditions (see Table 5.2). It was pointed out in Sec. 2.4 that Kumar and Kuloor have proposed a model by assuming the bubble formation to take place in two stages, namely, the expansion stage and the detachment stage. During the first stage, the bubble expands while its base remains attached to the orifice whereas in the detachment stage the bubble base moves away from the orifice and remains in contact with the orifice through a stem. This idealized model of bubble formation is quite similar to the behavior of forming a present first bubble. It is seen that the results presented in Table 5.3 show good agreement between the theoretical predictions and experimental values with a maximum deviation

Liquid	Orifice Dia. cm	Actual Flow Rate at Orifice cm ³ /sec	Bubble Departure Radius, R_d , cm		
			*Present Experiment	Theory	$\frac{\text{Experiment}}{\text{Theory}}$
Acetone	0.3	15.8	0.507	0.513	0.99
	0.3	34.8	0.684	0.666	1.03
Methanol	0.3	42.3	0.755	0.724	1.04
	0.4	56.3	0.802	0.829	0.98
Carbon Tetra- chloride	0.3	21.1	0.600	0.556	1.08
	0.3	37.9	0.671	0.704	0.95
Distilled Water	0.6	113.5	1.164	1.100	1.06
	0.6	180.1	1.329	1.320	1.01
Toluene	0.6	130.1	1.260	1.150	1.10

* R_d shown is the average of the three values presented in Table 5.2 for each actual flow rate.

Table 5.3 Comparison of Experimental Bubble Departure Radii with Predictions of Kumar and Kuloor[19]

of $9\frac{1}{2}\%$ in toluene.

5.3 Comparison of Present Barbotage and Nucleate Boiling

The quantitative comparison of bubble growth curves (R vs. t) between the present constant flow barbotage and nucleate boiling bubbles of Cole and Shulman[6] are presented in Figs. 5.21 to 5.25 for essentially the same bulk liquid temperatures. The saturation temperatures quoted in the figures for various liquids at the pressures stated by Cole and Shulman were obtained from Refs.[14,20,39] and are given to an accuracy of approximately half a degree Celsius to accommodate the discrepancy among the sources for the same conditions. Cole and Shulman indicated that bubble growth results varied in a statistical fashion for apparently the same conditions. In the figures, only the two boiling bubbles represented by the two extreme bubble growth curves (the uppermost and the lowest curves) are replotted for comparison with the present barbotage bubbles. Here it could be mentioned again that barbotage flow rates were chosen to give growth curves falling, for most of the growth time, roughly mid-way between the extremes of the growth curves for the boiling bubbles. The barbotage bubbles shown in the figures belong, in each case, to the bubble whose growth result lies the closest to the bubble growth Eqn. 2.4 among the three bubbles analyzed for the same conditions. Figures 5.26 to 5.30 give the bubble growth rates (dR/dt vs. t , or $\dot{R}$ vs. t) of the boiling and barbotage bubbles. The growth rates were obtained for both

Acetone

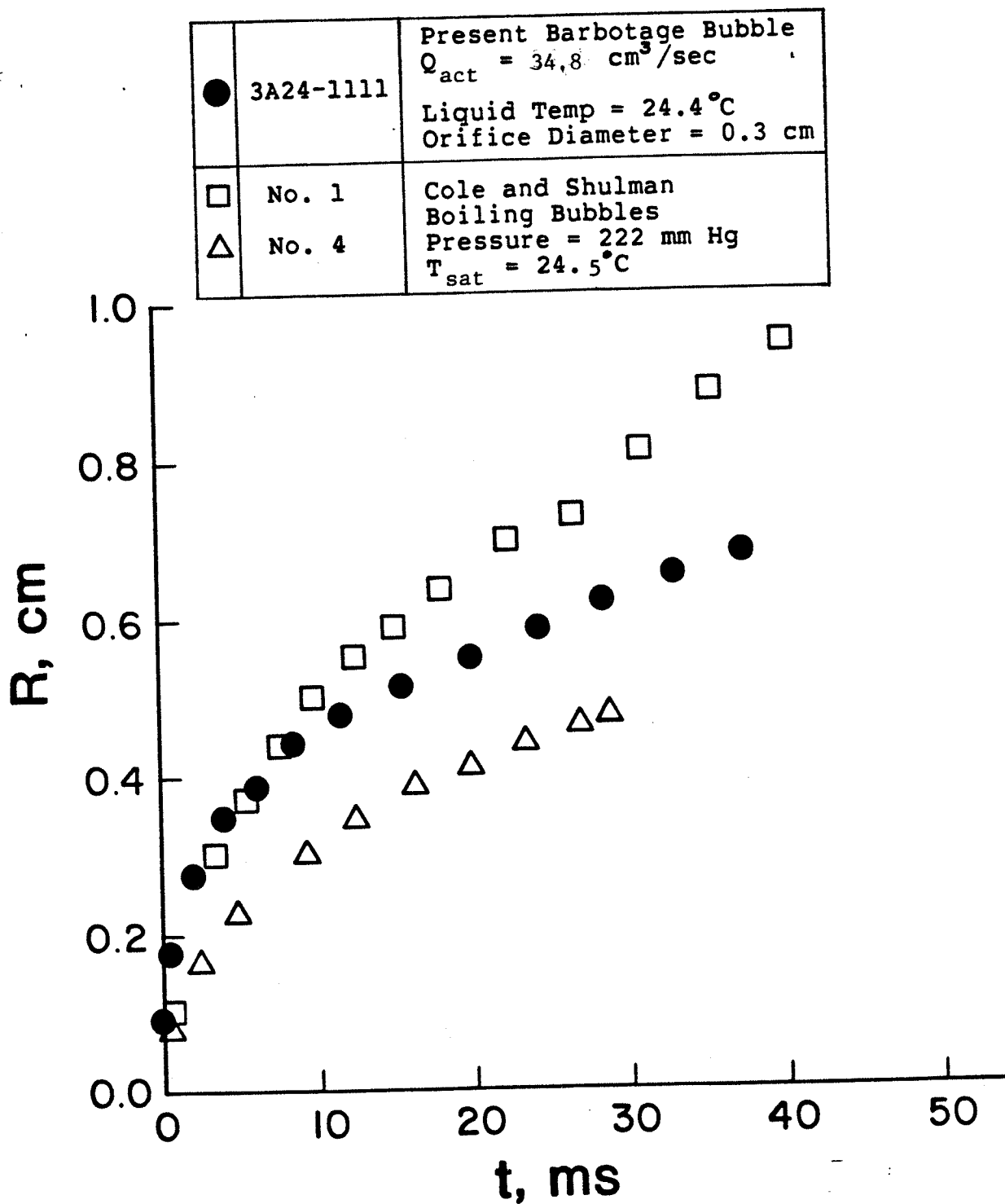


Fig. 5.21 Comparison of Bubble Growth Curves Between Present Barbotage and Boiling Bubbles for Acetone.

Methanol

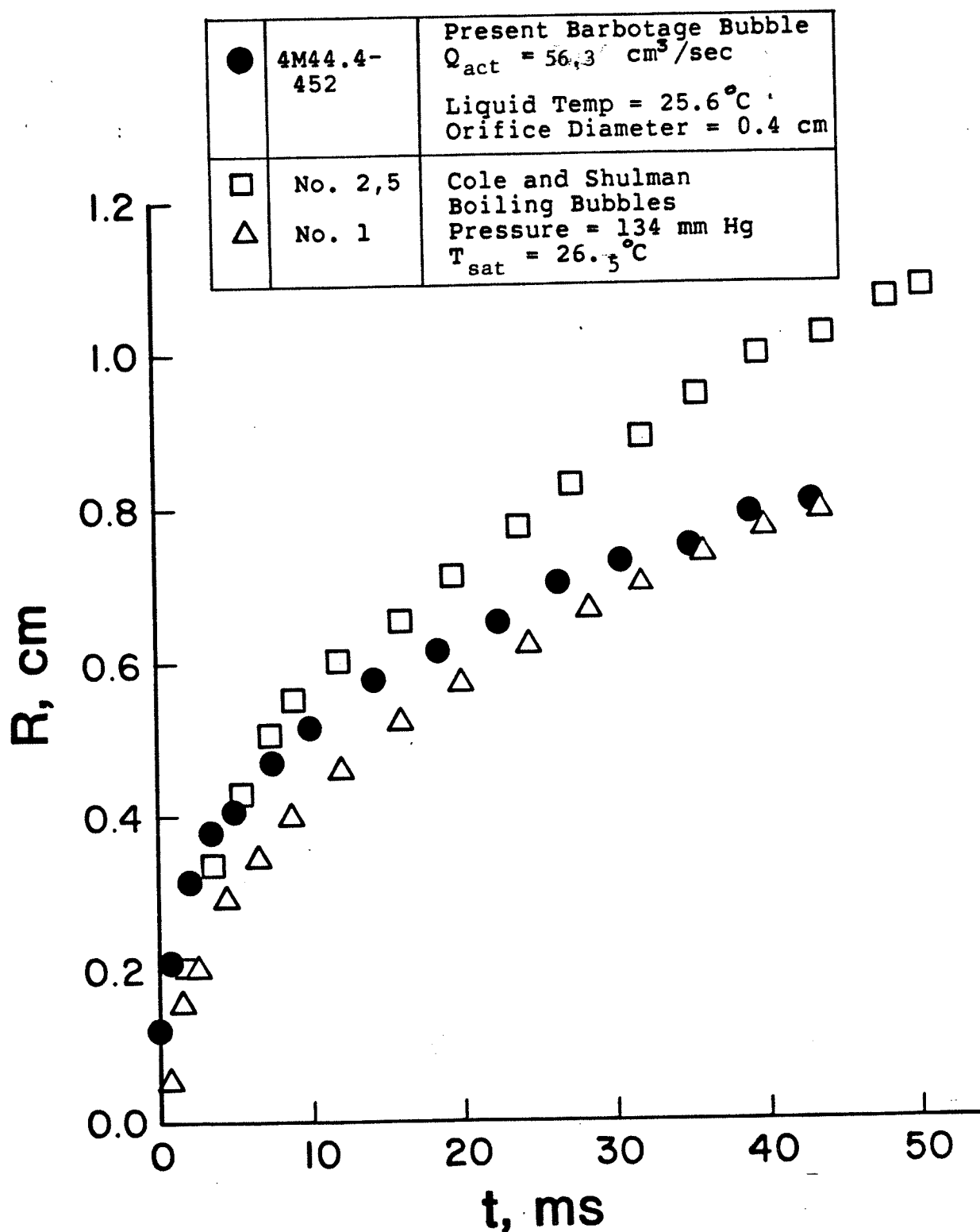


Fig. 5.22 Comparison of Bubble Growth Curves Between Present Barbotage and Boiling Bubbles for Methanol.

Carbon Tetrachloride

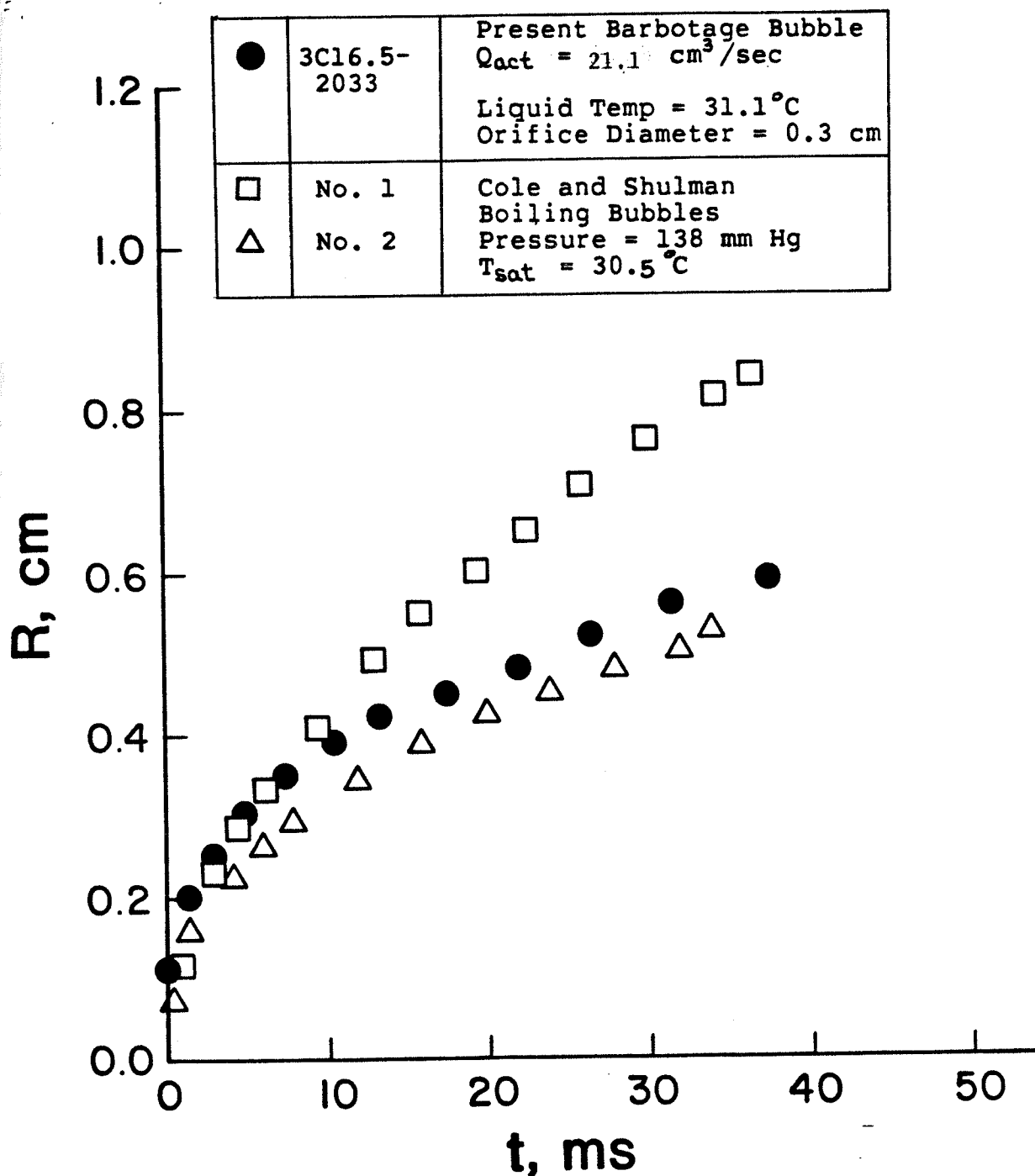


Fig. 5.23 Comparison of Bubble Growth Curves between Present Barbotage and Boiling Bubbles for Carbon Tetrachloride.

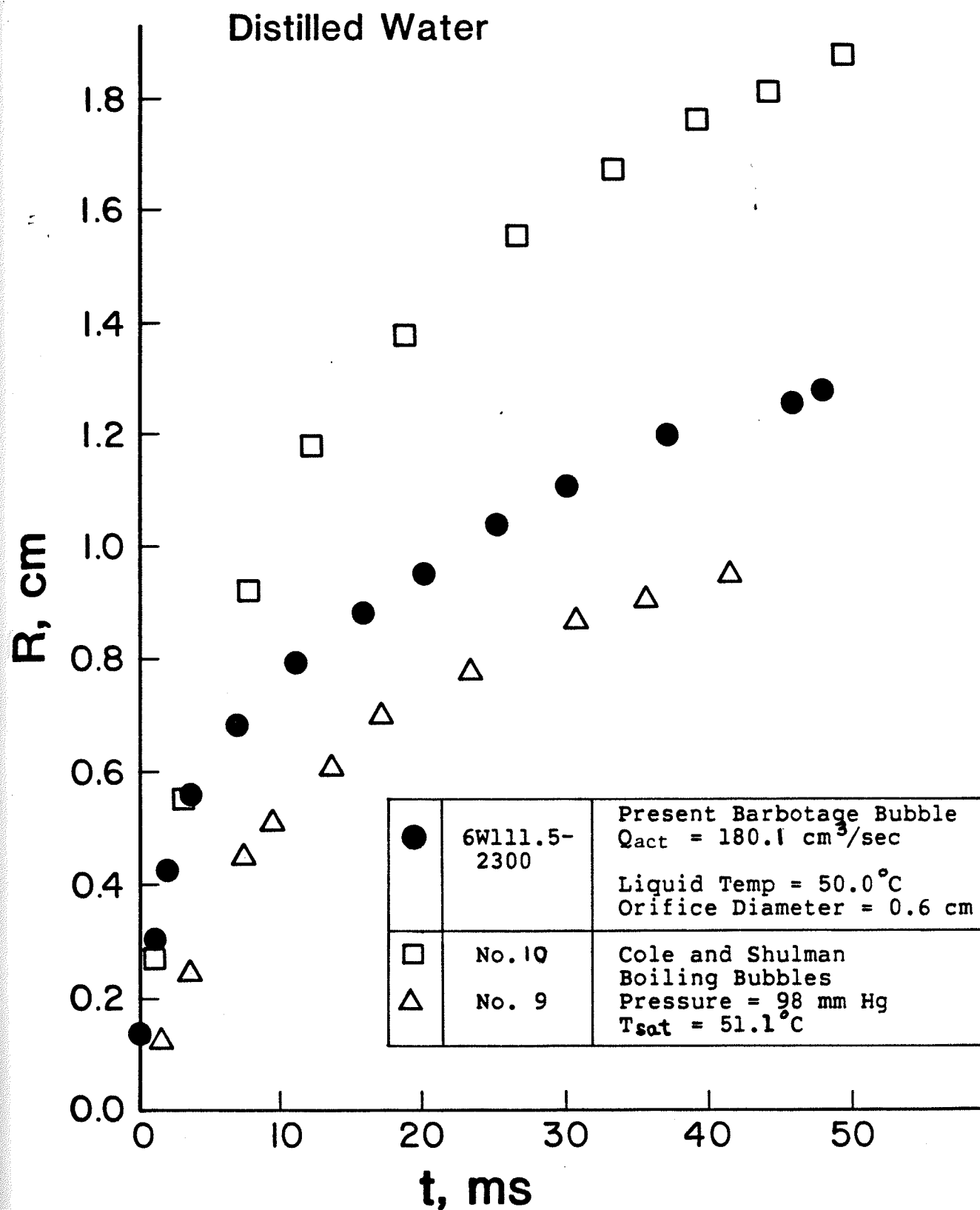


Fig. 5.24 Comparison of Bubble Growth Curves Between Present Barbotage and Boiling Bubbles for Distilled Water.

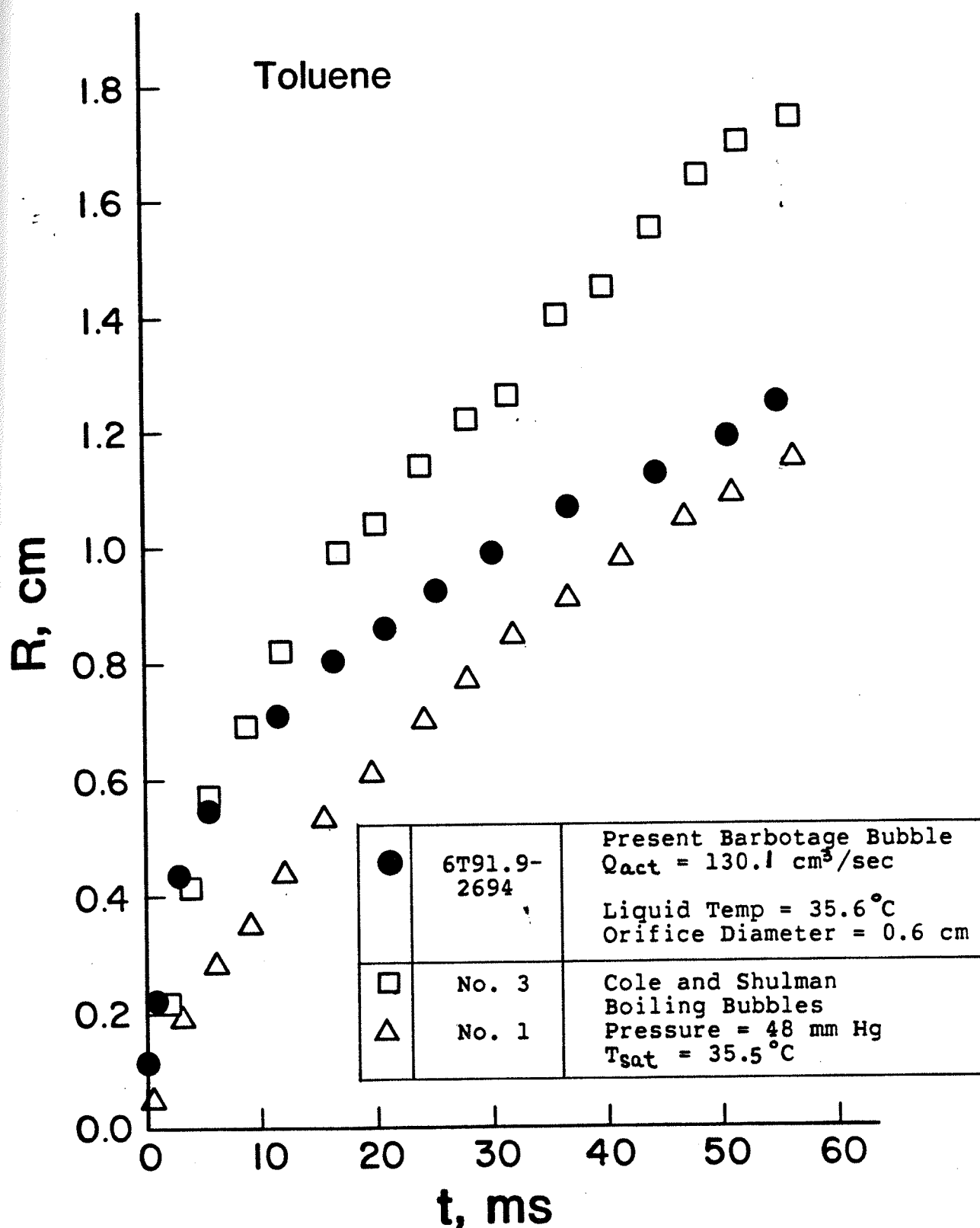


Fig. 5.25 Comparison of Bubble Growth Curves Between Present Barbotage and Boiling Bubbles for Toluene.

Acetone

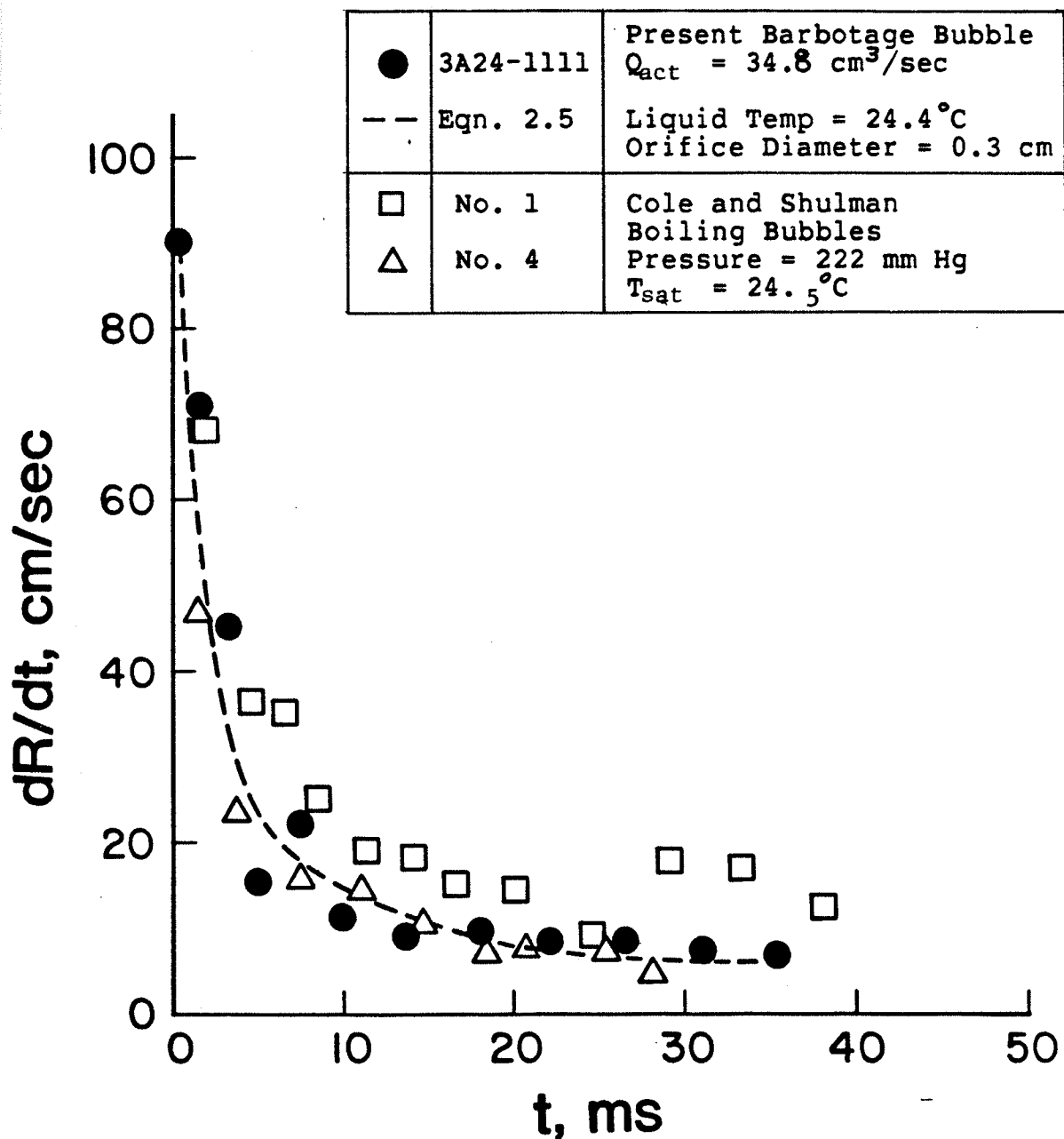


Fig. 5.26 Comparison of Bubble Growth Rates Between Present Barbotage and Boiling Bubbles for Acetone.

Methanol

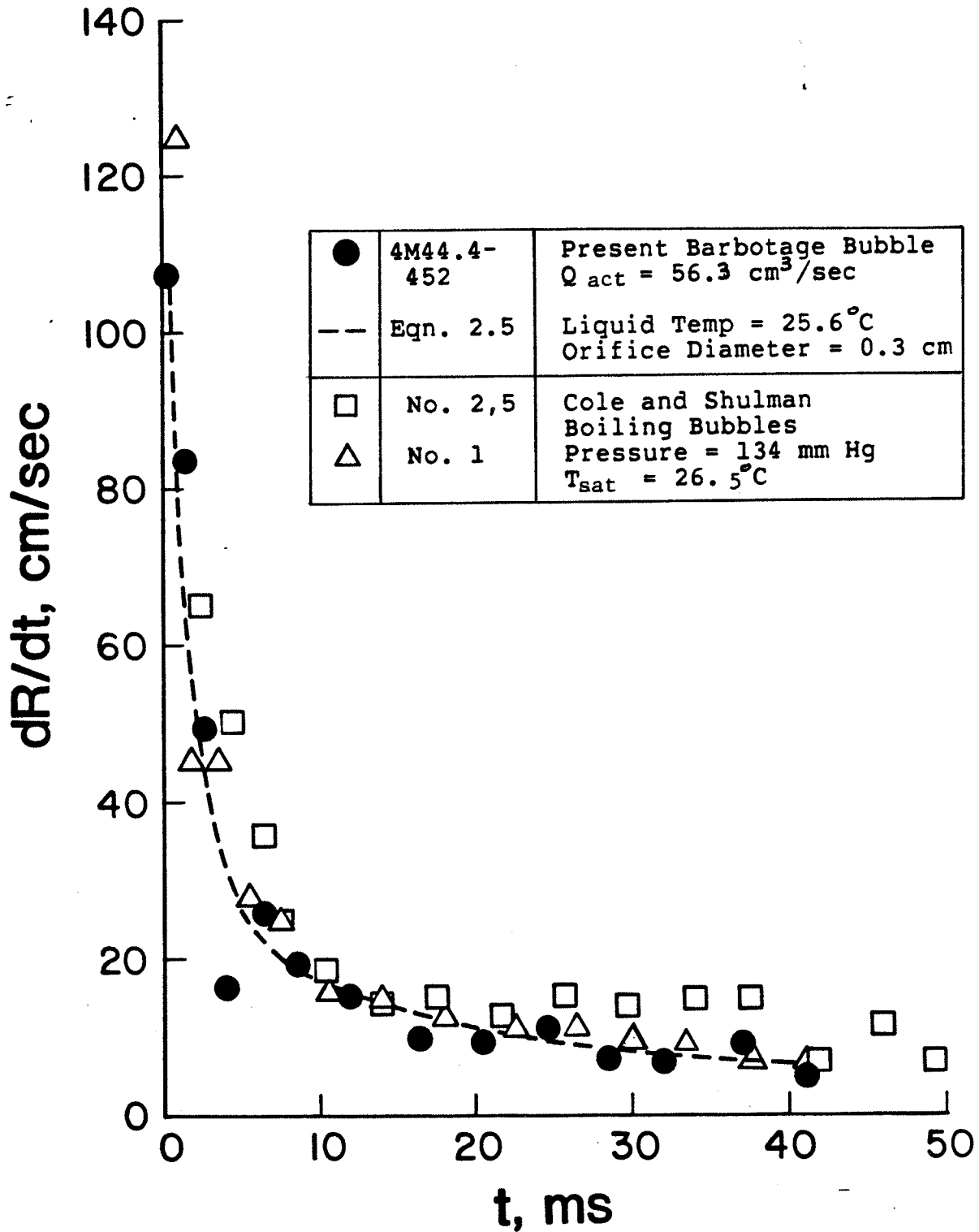


Fig. 5.27 Comparison of Bubble Growth Rates Between Present Barbotage and Boiling Bubbles for Methanol.

Carbon Tetrachloride

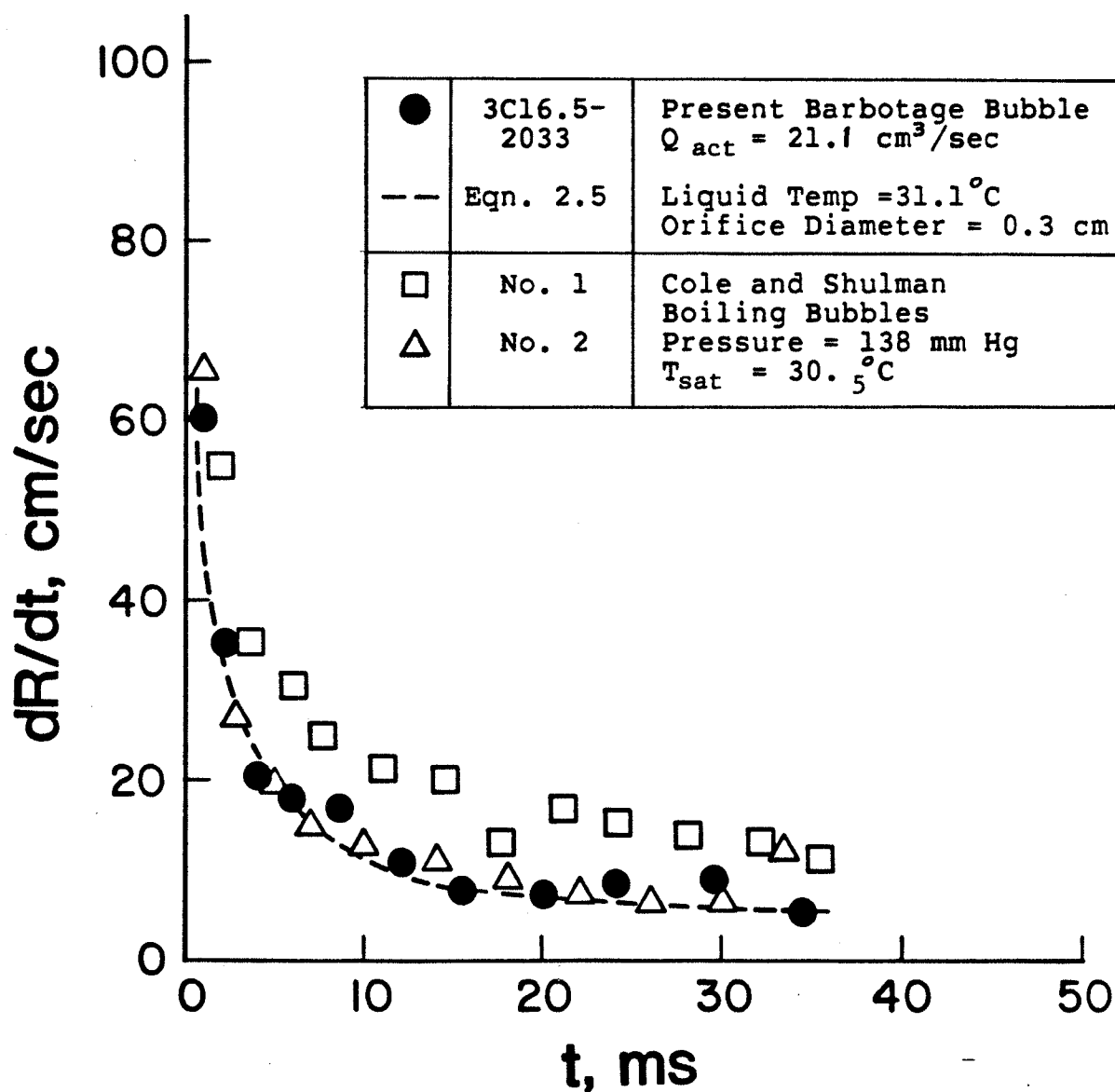


Fig. 5.28 Comparison of Bubble Growth Rates Between Present Barbotage and Boiling Bubbles for Carbon Tetrachloride.

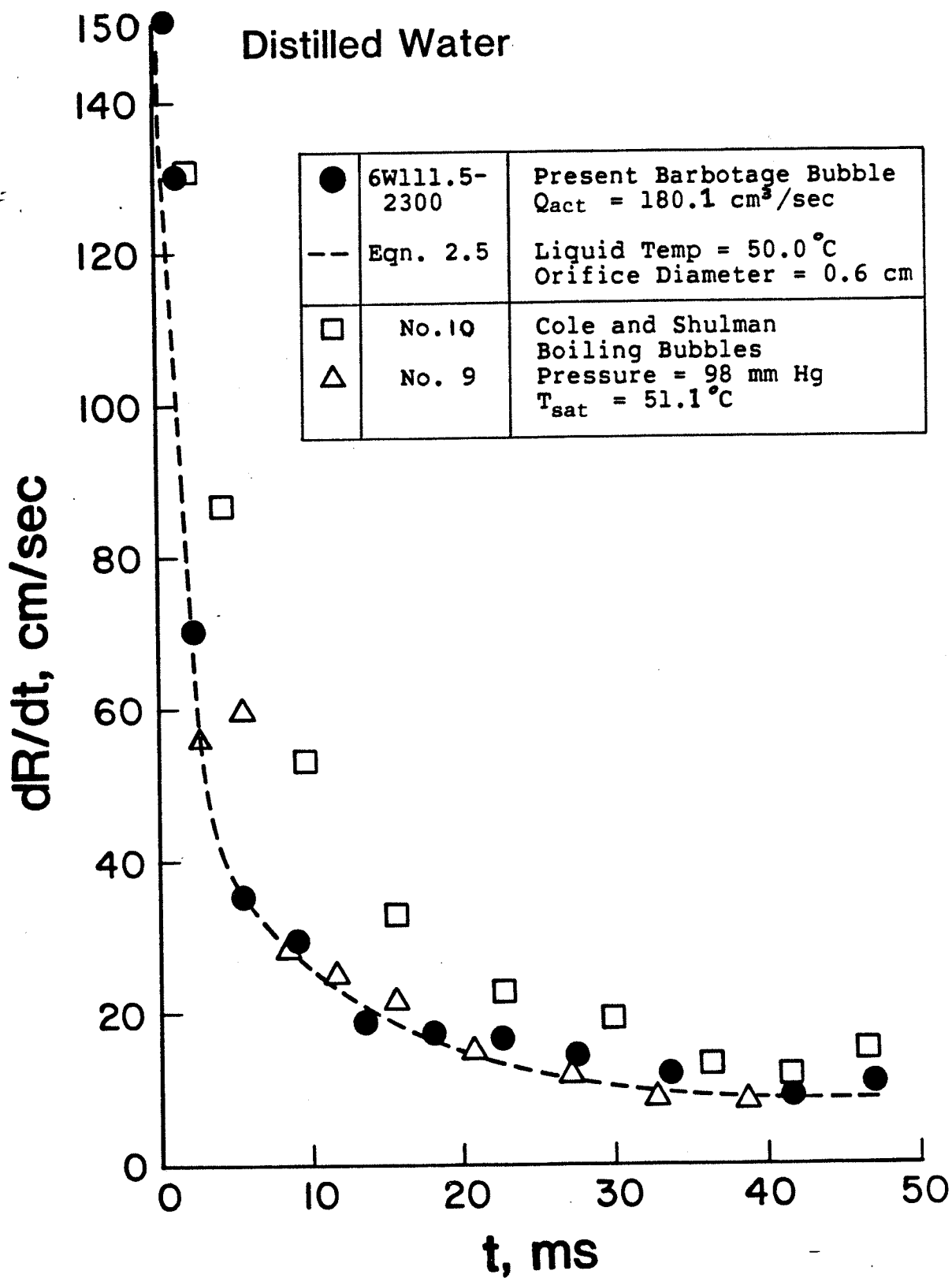


Fig. 5.29 Comparison of Bubble Growth Rates Between Present Barbotage and Boiling Bubbles for Distilled Water.

Toluene

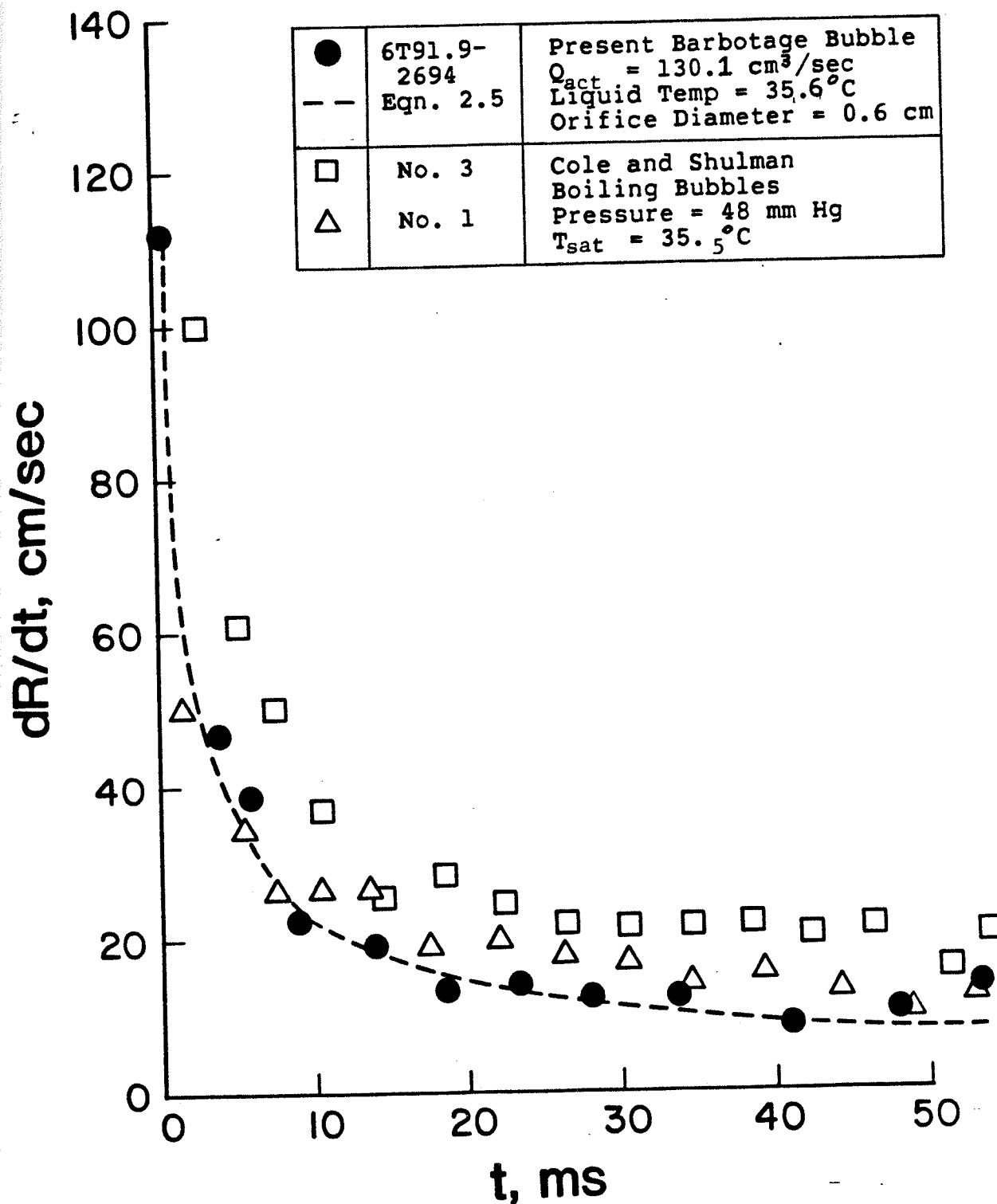


Fig. 5.30. Comparison of Bubble Growth Rates Between Present Barbotage and Boiling Bubbles for Toluene.

boiling and barbotage by measuring the slope, $\Delta R/\Delta t$, between two consecutive R vs. t data points and plotting this at the mean of the time of the two data points. Along with the barbotage bubbles, Eqn. 2.5 for constant-flow barbotage bubble growth rates is shown. The following observations can be made regarding these figures:

(i) The growth curves (R vs. t) of barbotage bubbles are slightly higher than those of the two boiling bubbles during the early part of the growth period and have shapes similar to those of the boiling bubbles for most of the growth time. Cole and Shulman[5] indicated that the bubble growth shapes (R vs. t) of their boiling results were best described by the square root of time variation whereas the shapes of the present barbotage bubbles growth vary with the cube root of time as indicated in Eqn. 2.4 and the previous Sec. 5.2.2. Further, in boiling, the bubble growth depends on the fluid properties and superheat conditions while in constant-flow barbotage, the bubble growth is simply controlled by the gas flow rate.

(ii) The plots of the bubble growth rates ($\dot{R}$ vs. t) show that the growth rates of barbotage bubbles appear to have shapes quite similar to those of the two boiling bubbles with the magnitudes approximately the same as the lower boiling bubble except in toluene where the barbotage bubble shows rather lower growth rates than the boiling bubbles.

(iii) Table 5.4 gives a comparison of bubble departure radii between the present barbotage and boiling bubbles

Liquid	Boiling (Cole and Shulman) Range of Bubble Departure Radius, R_d , cm	Barbotage (Present) Bubble Departure Radius, R_d^* , cm
Acetone	0.48 - 0.95	0.69
Methanol	0.80 - 1.09	0.80
Carbon Tetrachloride	0.53 - 0.84	0.60
Distilled Water	0.95 - 1.88	1.33
Toluene	1.15 - 1.79	1.26

* Average for the three bubbles analyzed for any set of conditions (see Table 5.2).

Table 5.4 Comparison of Bubble Departure Radii between the Present Barbotage and Boiling Bubbles

presented in Figs. 5.21 to 5.25. The bubble departure radii for barbotage bubbles are the average of the three bubbles analyzed for each set of conditions (see Table 5.2). It is seen that the departure radii of barbotage bubbles fall within the range of those for the boiling bubbles at nominally the same conditions.

The above observations of bubble growth curves (R vs. t) and bubble growth rates (dR/dt vs. t) reveal that there are some similarities between the present barbotage and boiling bubbles regarding both the shape and magnitude of these curves. The present barbotage bubbles also give a reasonably good "combination" of R vs. t and $\dot{R}$ vs. t in comparison with boiling bubbles. For the same liquid properties in boiling and barbotage, the combination referred to means: a bubble growth curve (R vs. t) for barbotage roughly mid-way between the extremes of the boiling data for a substantial portion of the growth time; and barbotage growth rates ($\dot{R}$ vs. t) which fall close to the lower boiling data.

As regards constant-flow barbotage as a simulation of nucleate pool boiling, it should be noted that there is a limitation on the exponent in $R \sim t^n$. As mentioned earlier, Cole and Shulman used

$$R = 2.5Ja^{3/4} \sqrt{\alpha t}$$

to correlate their boiling data, or $R \sim t^{1/2}$. The simple

barbotage system used here results in $R \sim t^{1/3}$ in which the time exponent is different from that in boiling. (It should be noted that, however, as pointed out in Sec. 2.2.2, a wide range of n in $R \sim t^n$ have been reported for boiling.)

Further, if it is desired to use barbotage systems conveniently for the simulation of particular boiling conditions (i.e., the liquid temperature to be the same as the saturation temperature in boiling), the boiling saturation temperature must be low enough to allow for the operation of barbotage systems at atmospheric pressure (the most convenient pressure for operation); this often implies low-pressure boiling conditions.

The departure radii in boiling and barbotage as obtained here are similar (see Table 5.4), i.e. the barbotage results fall within the range of the boiling results.

CHAPTER 6

SUMMARY AND CONCLUSIONS

(1) Barbotage experiments under constant-flow conditions were devised in which it was possible to compare the hydrodynamics of the present barbotage bubbles with nucleate boiling results of Cole and Shulman[6] for essentially the same bulk liquid properties. The hydrodynamics referred to here were bubble growth (R vs. t), bubble growth rate (dR/dt vs. t), and bubble departure radius. A barbotage flow rate, in each condition, was chosen to give the growth curve (R vs. t) falling within the two extremes of the growth curves (the uppermost and the lowest curves) of boiling bubbles for most of the growth time. The experiments were performed in acetone, methanol, carbon tetrachloride, distilled water, and toluene (the same liquids as used by Cole and Shulman). Air was used as the injected gas. High-speed photography was employed to record the sequence of bubble formation. The volume of a bubble at any instant during formation was determined from the frames of the high speed motion picture in the manner described by L'Ecuyer and Murthy[23].

(2) Three types of bubble formation were distinguished in the present study. They were the formation of double bubbles, three-bubble series, and series of more than three bubbles. In general, the bubble formation of the last type, long bubble series, could be broken down into: a number of double bubbles, three-bubble series, or combinations of some

double bubbles and three-bubble series. The first bubbles of the three types were chosen to be analyzed for measuring the bubble volumes against time.

(3) The bubble growth Eqn. 2.4 for constant-flow barbotage is presented in Chapter 2, Literature Review. The comparison of barbotage R vs. t results with Eqn. 2.4 indicated that the apparatus indeed generated constant-flow bubbles.

(4) The measured bubble departure radii of the present work were compared with the theoretical predictions based on the model of Kumar and Kuloor[22]. The theoretically predicted bubble departure radii were found to be in good agreement with the experimental results with a maximum deviation of $9\frac{1}{2}\%$ in toluene.

(5) Quantitative comparisons of the hydrodynamics between the present barbotage bubbles and boiling bubbles of Cole and Shulman are presented in Figs. 5.22 to 5.31 and Table 5.4. The conclusions drawn are as follows:

- (i) The growth curves (R vs. t) of barbotage bubbles are slightly higher than those of the two boiling bubbles during the early part of the growth period, but then lie roughly mid-way between the extremes of the boiling results for the major portion of the growth time.
- (ii) Considering the scatter in the actual $\dot{R}$ vs. t results (Figs. 26 to 30), the barbotage and the lower boiling results lie very close together except for toluene where the barbotage results are distinguishably lower

than the boiling results.

- (iii) The departure radii of barbotage bubbles fall within the range of those for boiling at nominally the same conditions.

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APPENDICES

APPENDIX A

REPEATABILITY TESTS

Repeatability tests were performed on methanol and distilled water with essentially the same flow rates, orifice diameters and liquid bulk temperatures as those employed in the experiments with the same liquids reported in the body of this thesis. Figures A.1 and A.2 show the comparison of bubble growth results (R vs. t) between the repeatability tests and the original experimental work. It is seen that the bubble growth results of the repeatability tests for both liquids are in good agreement with those of original experiments. A quantitative measure of the repeatability is given below where the experimental R vs. t data are compared with Eqn. 2.4 for the original experimental conditions; the algebraic mean deviation, $\bar{d}$ and root mean square deviation, $\bar{d}_{rms}$ are given in each case:

Distilled water

Original experiment:	Bubble 6W111.5-1833	$\bar{d} = 5.5\%$, $\bar{d}_{rms} = 8.7\%$
	Bubble 6W111.5-1994	$\bar{d} = 5.3\%$, $\bar{d}_{rms} = 7.0\%$
	Bubble 6W111.5-2300	$\bar{d} = -0.8\%$, $\bar{d}_{rms} = 5.0\%$

Repeatability test:	Bubble 6W111.5R-1276	$\bar{d} = 1.0\%$, $\bar{d}_{rms} = 5.2\%$
	Bubble 6W111.5R-2038	$\bar{d} = 0.7\%$, $\bar{d}_{rms} = 1.5\%$

Methanol

Original experiment:	Bubble 3M35-800	$\bar{d} = 1.6\%$, $\bar{d}_{rms} = 4.0\%$
	Bubble 3M35-1749	$\bar{d} = 2.4\%$, $\bar{d}_{rms} = 3.5\%$
	Bubble 3M35-2640	$\bar{d} = -1.8\%$, $\bar{d}_{rms} = 7.1\%$

Repeatability	Bubble 3M35R-2814	$\bar{d} = 2.0\%$, $\bar{d}_{rms} = 6.4\%$
test:	Bubble 3M35R-1784	$\bar{d} = 0.7\%$, $\bar{d}_{rms} = 2.4\%$

It can be seen that all the original and repeatability data fall with an algebraic mean deviation in the range of -1.8 to 5.5% and a root mean square deviation in the range of 1.5 to 8.7%.

Table A.1 and A.2 gives the tabulated results of the repeatability tests for both distilled water and methanol respectively. The letter "R" right after the indicated air flow rate in the bubble identification numbers (see Appendix F for explanation) shown in both tables and figures indicates a repeatability test. These repeatability tests were run after the main experimental program, i.e., after obtaining the data reported in the body of the thesis.

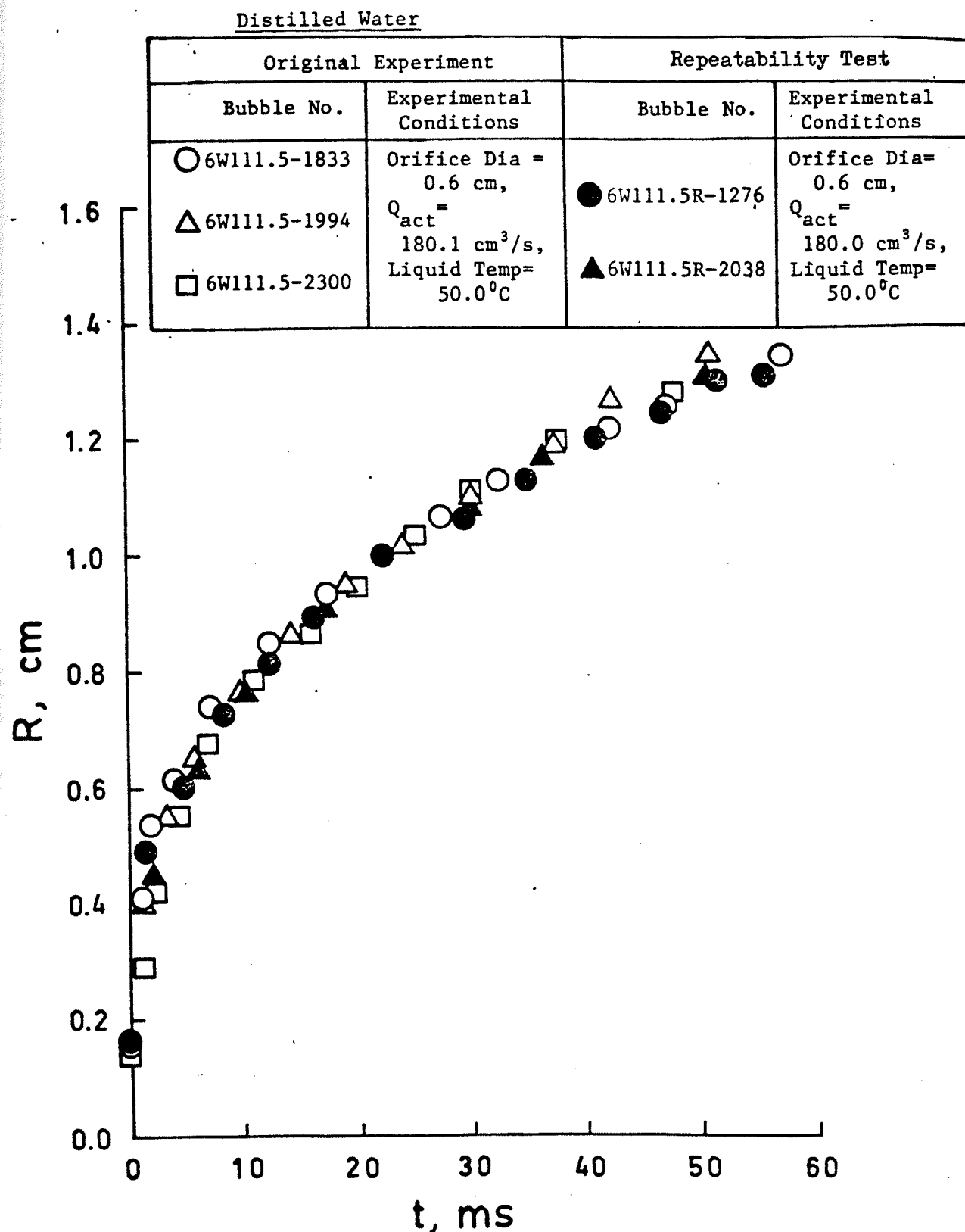


Fig. A.1 Comparison of the Bubble Growth Curves between the Repeatability Test and the Original Experimental Results for Distilled Water.

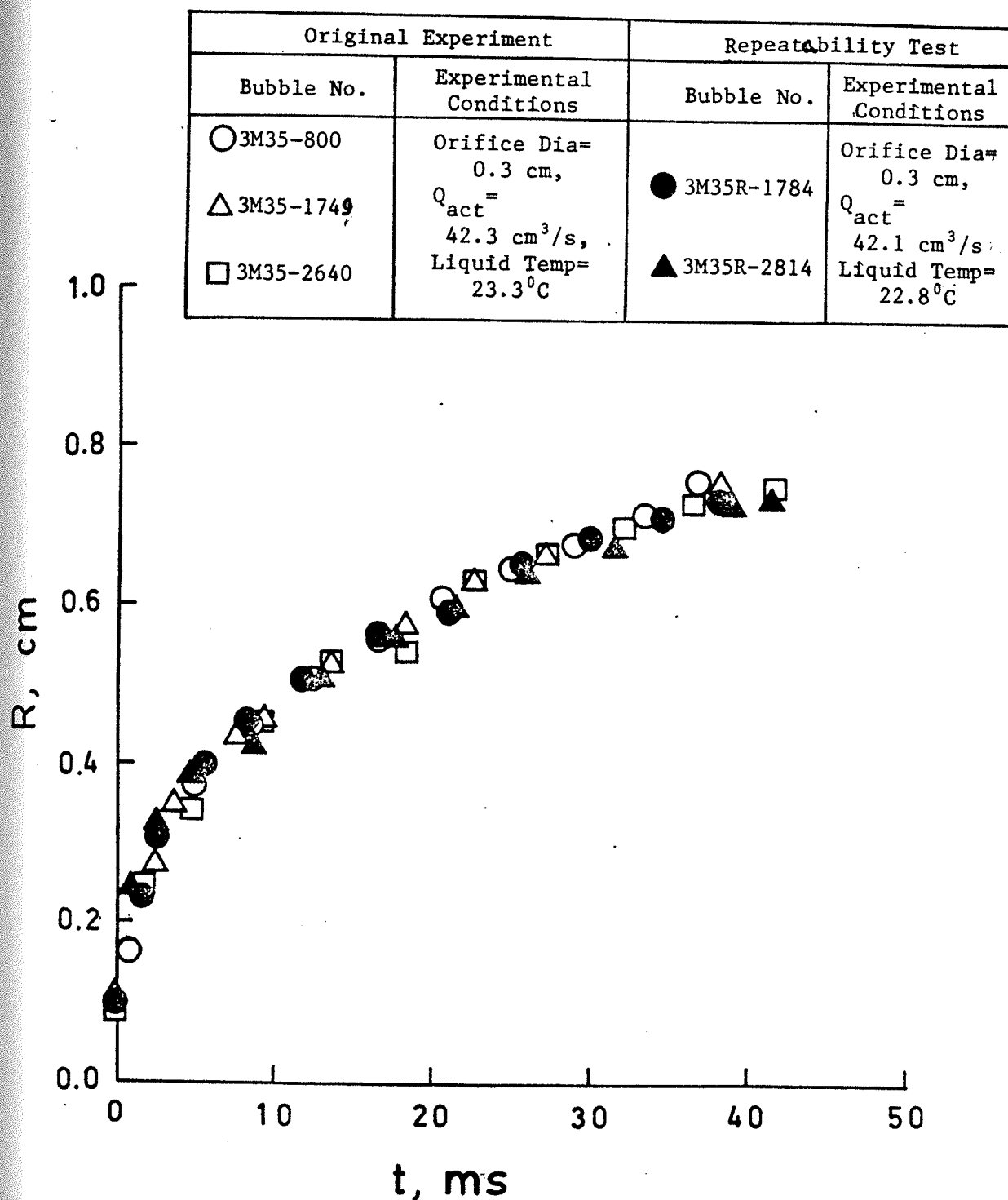
Methanol

Fig. A.2 Comparison of the Bubble Growth Curves between the Repeatability Test and the Original Experimental Results for Methanol

Table A.1 Repeatability Test: Bubble Growth Data for Distilled Water
(Actual Flow Rate, $180.0 \text{ cm}^3/\text{sec}$).

Orifice diameter:	0.6 cm
Liquid temperature:	50.0 °C
Room temperature:	23.0 °C
Liquid height above the orifice:	12.0 cm
Indicated air flow rate:	111.5 cm^3/sec

Bubble Identification No. 6W111.5R-1276
(Time/frame, $4.167 \times 10^{-4} \text{ sec/frame}$)

Frame No.	Time ms	Bubble Volume $\text{cm}^3 \times 10^{-3}$	Bubble Equiv. Radius cm
1276	0.0	18.15	0.163
1280	1.7	491.60	0.490
1287	4.6	890.05	0.597
1296	8.3	1592.84	0.724
1306	12.5	2240.85	0.812
1316	16.7	2995.00	0.894
1330	22.5	4067.53	0.990
1345	28.8	5014.50	1.062
1360	35.0	6038.28	1.129
1375	41.3	7251.93	1.201
1390	47.5	8134.60	1.248
1405	53.8	9080.16	1.294
1410	55.8	9397.43	1.309

Bubble Identification No. 6W111.5R-2038
(Time/frame, $4.762 \times 10^{-4} \text{ sec/frame}$)

2038	0.0	12.76	0.145
2042	1.9	384.21	0.451
2050	5.7	1005.04	0.632
2060	10.5	1961.22	0.777
2075	17.6	3152.10	0.910
2085	22.4	3860.54	0.973
2100	29.5	5333.57	1.084
2115	36.7	6711.12	1.170
2130	43.8	8139.51	1.248
2145	51.0	9408.04	1.310
2156	56.2	10204.91	1.340

Table A.2 Repeatability Test: Bubble Growth Data for Methanol
(Actual Flow Rate, 42.1 cm³/sec).

Orifice diameter:	0.3 cm
Liquid temperature:	22.8 °C
Room temperature:	22.8 °C
Liquid height above the orifice:	12.0 cm
Indicated air flow rate:	35.0 cm ³ /sec

Bubble Identification No. 3M35R-1784
(Time/frame, 4.545 x 10⁻⁴ sec/frame)

Frame No.	Time ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
1784	0.0	3.85	0.097
1787	1.4	52.19	0.232
1790	2.7	121.70	0.307
1796	5.5	248.97	0.390
1802	8.2	377.38	0.448
1810	11.8	534.18	0.503
1820	16.4	741.48	0.561
1830	20.9	848.93	0.587
1840	25.5	1132.86	0.647
1850	30.0	1325.38	0.681
1860	34.5	1478.55	0.707
1868	38.2	1631.65	0.730

Bubble Identification No. 3M35R-2814
(Time/frame, 4.348 x 10⁻⁴ sec/frame)

2814	0.0	2.45	0.084
2816	0.9	61.23	0.245
2820	2.6	146.87	0.327
2825	4.8	239.45	0.385
2834	8.7	312.08	0.421
2844	13.0	572.09	0.515
2854	17.4	727.86	0.558
2864	21.7	874.03	0.593
2874	26.1	1090.76	0.639
2884	31.4	1260.45	0.670
2894	34.5	1481.90	0.707
2904	39.1	1603.57	0.726
2909	41.3	1641.75	0.732

APPENDIX B

CALIBRATION OF THE ROTAMETER

The rotameter (Brook Instrument Co., Model 1560, Tube No. 2-2-25C) was calibrated using a gas meter manufactured by Precision Scientific Co., USA. The arrangement of the calibration apparatus is given in Fig. B.1. The wet gas meter was filled with distilled water to the required level before the calibration. The compressed air passing through the pressure regulator valve reduced in pressure to the operating condition. The air then passed through a filter, gas dryer and rotameter. Finally, the air entered the wet gas meter where the volumetric flow rate of the air which was saturated with water vapor was measured. The line pressure between the rotameter and the wet gas meter was recorded; room temperature, wet gas meter temperature, and barometric pressure were also recorded before and after the calibration process. The measured saturated air flow rate was corrected for vapor content, then corrected to standard conditions (14.7 psia and 70 °F) as described below for comparison with the manufacturer's calibration curve for the rotameter. Calculations, etc., in this appendix are in Imperial units since the manufacturer's materials were in these units.

Determination of the dry air flow rate at the wet gas meter

Since the air passing through the wet gas meter was saturated with water vapor, it was necessary to correct the

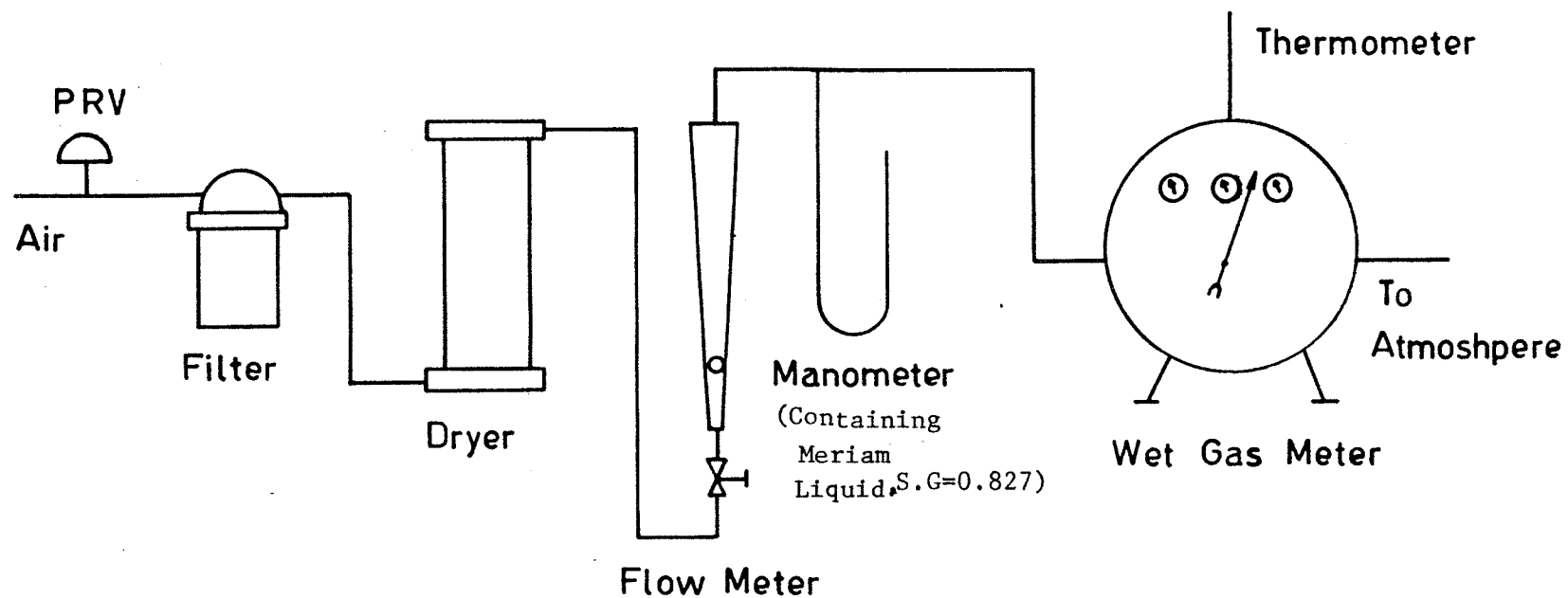


Fig B.1 Calibration Apparatus Arrangement for Rotameter.

measured flow rate to dry air conditions. It is well known from thermodynamics that in a mixture of ideal gases, the volume fraction of one component is equal to the ratio of the partial pressure of that component at the temperature of the mixture to the total pressure of the mixture. That is

$$\frac{Q_{\text{vap}}}{Q_{\text{mix}}} = \frac{Q_{\text{vap}}}{Q_{\text{vap}} + Q_{\text{air}}} = \frac{P_{\text{vap}}}{P_{\text{tot}}} \quad \text{B.1}$$

where Q_{air} , Q_{vap} , and Q_{mix} are the volumetric flow rates of air, water vapor and mixture (vapor + air), respectively. P_{vap} is the partial pressure of the vapor and P_{tot} is the total pressure of the mixture. Thus, the dry air flow rate, Q_{air} can be obtained from Eqn. B.1 with known values of the mixture flow rate, temperature and pressures (P_{vap} and P_{tot}).

Correction of the air flow rate at the wet meter to air flow rate at rotameter operating conditions

The air flow rate at the wet meter Q_{air} is related to the air flow rate at rotameter conditions through

$$Q_{\text{m}} = Q_{\text{air}} \times \frac{P_{\text{wet meter}} \times T_{\text{m}}}{P_{\text{m}} \times T_{\text{wet meter}}} \quad \text{B.2}$$

where Q_{m} = Air flow rate at rotameter conditions,

T_{m} = Temperature at rotameter,

P_{m} = Pressure at rotameter,

Q_{air} = Air flow rate at wet gas meter conditions,

$T_{\text{wet meter}}$ = Temperature at wet gas meter,

$P_{\text{wet meter}}$ = Pressure at wet gas meter

In the present case, the pressures at the rotameter and in the wet gas meter are essentially the same, as are the temperatures, i.e. $P_m \approx P_{\text{wet meter}}$ and $T_m \approx T_{\text{wet meter}}$. We therefore have

$$Q_m \approx Q_{\text{air}}$$

Correction of air flow rate at rotameter operating conditions to standard conditions

For comparison with the manufacturer's calibration curve a further correction is necessary [B.1*,B.2] through

$$Q'_I = Q_m \sqrt{\frac{\text{S.G.} \times (70.0 + 459.7) \times P_m}{1.0 \times T_m \times 14.7}} \quad \text{B.3}$$

where Q'_I is the volumetric air flow rate at standard conditions (14.7 psia and 70 F) for the same float height. In this equation P_m would be in psia and T_m in °R.

Example

Indicated rotameter air flow rate (scale)	= 3 cm
Measured flow rate at wet meter, Q_{mix}	= 1.84 ft ³ /hr
P_{tot} ($P_{\text{wet meter}}$ + P_{atm})	= 14.19 psia
Temperature at wet gas meter, $T_{\text{wet meter}}$	= 65.0 °F
Water vapor at 65 F, P_{vap}	= 0.31 psia
Temperature at rotameter (room temp.), T_m	= 65.2 °F
Specific gravity of air, S.G.	= 1.0

Substituting the values of Q_{mix} , P_{tot} , and P_{vap} in Eqn. B.1,

*Equation quoted requires additional development in order to obtain Eqn. B.3

we have

$$\frac{Q_{\text{vap}}}{Q_{\text{mix}}} = \frac{Q_{\text{vap}}}{Q_{\text{vap}} + Q_{\text{air}}} + \frac{0.31}{14.19} = 0.0218$$

Therefore,

$$\begin{aligned} Q_{\text{vap}} &= 0.0218 \times Q_{\text{mix}} = 0.0218 \times 1.84 \\ &= 0.04 \text{ ft}^3/\text{hr} \end{aligned}$$

Thus, the air flow rate is

$$\begin{aligned} Q_{\text{air}} &= Q_{\text{mix}} - Q_{\text{vap}} = 1.84 - 0.04 \\ &= 1.80 \text{ ft}^3/\text{hr} \end{aligned}$$

As indicated earlier, in the present case essentially $Q_m = Q_{\text{air}}$. Substituting Q_m into Eqn. B.3, we obtain

$$\begin{aligned} Q_I' &= 1.80 \sqrt{\frac{1.0 \times 14.19 \times (70.0 + 459.7)}{1.0 \times 14.7 \times (65.2 + 459.7)}} \\ &= \underline{1.78} \text{ ft}^3/\text{hr} \end{aligned}$$

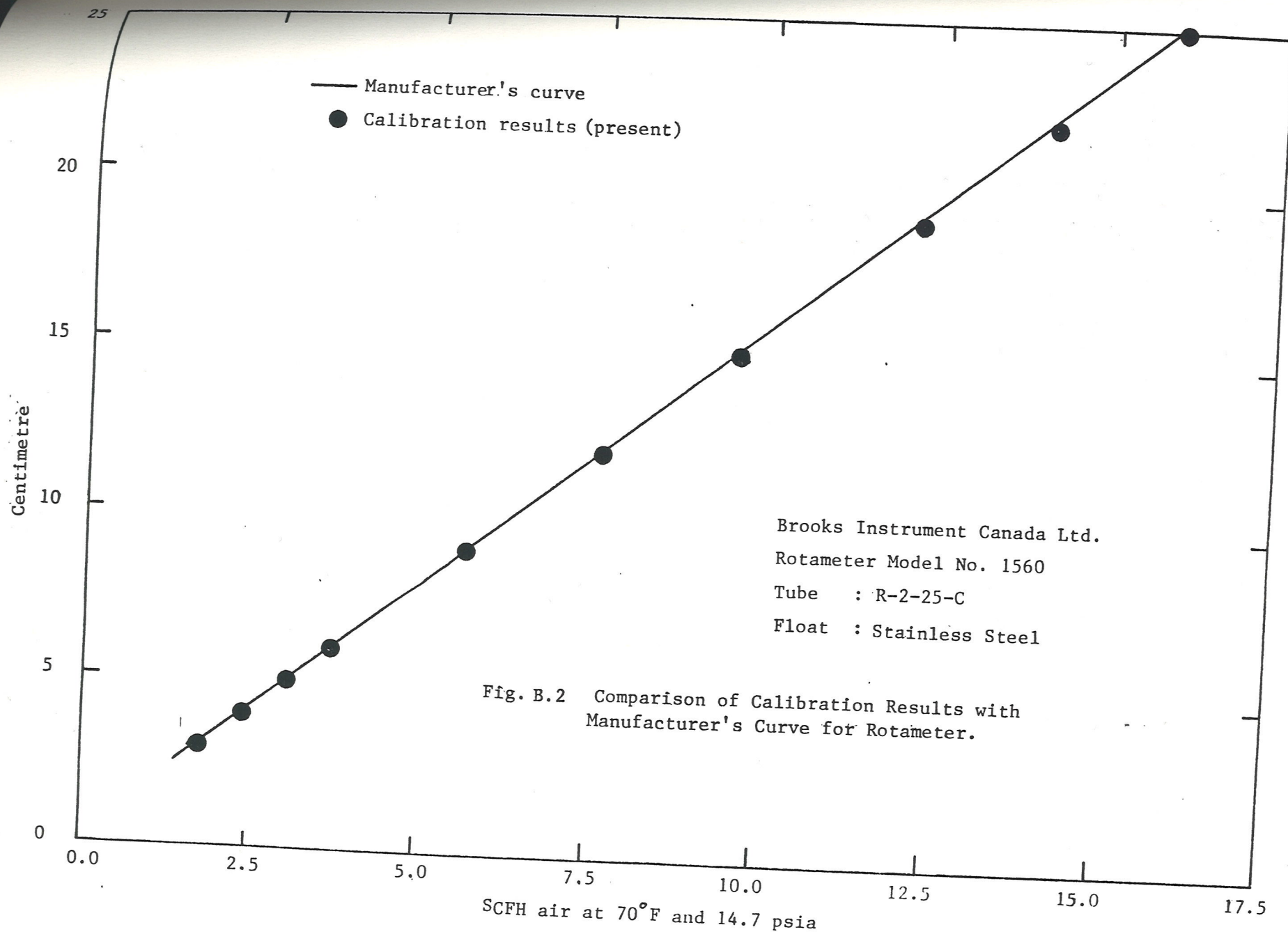
Table B.1 summarizes the operating conditions and calibration results for ten values of air flow rate. The corrected values of air flow rate at standard conditions are plotted on the manufacturer's calibration curve and are shown in Fig. B.2. It is seen that the calibration results are in excellent agreement with the manufacturer's curve. Therefore, the manufacturer's curve was used to obtain the indicated air flow rates for the the present barbotage experiments.

Rotameter calibrated : Brook Instrument, Model 1560
 Tube No. R-2-25-C
 Wet gas meter : Precision Scientific Co.
 Barometric pressure : Start 14.18 psia; End 14.18 psia
 Room temperature : Start 65.2 °F; End 65.2 °F
 Standard conditions : 70.0 °F and 14.7 psia

Temperature at wet gas meter : 65.0 °F

Rotameter	Wet gas meter		
Air flow rate - cm scale	$\Delta P_{\text{wet meter}}$ in. of liquid (S.G. = 0.827)	Q_{mix} Vap. + air (ft ³ /hr)	Q_1 at standard conditions
3	0.20	1.84	1.78
4	0.25	2.52	2.44
5	0.25	3.18	3.07
6	0.30	3.85	3.72
9	0.35	5.84	5.64
12	0.40	7.86	7.59
15	0.45	9.95	9.60
19	0.60	12.68	12.24
22	0.70	14.69	14.18
25	0.80	16.52	15.96

Table B.1 Operating Conditions and Calibration Results.



References for Appendix B

B.1 Brooks Instruments General Catalog, P.50,
(Identification on back cover 1171-B-5M-B)

B.2 VARIABLE AREA FLOWMETER HANDBOOK:

Vol. 1, BASIC ROTAMETER PRINCIPLES, Fisher and
Porter Catalog 10A 1021 (1970); Vol. 2, ROTAMETER
CALCULATIONS, Fisher and Porter Catalog 10A 1022
(1969).

APPENDIX C

PHYSICAL PROPERTIES OF THE EXPERIMENTAL LIQUIDS

The properties of the liquids used in the present experiments are listed in Table C.1. The properties for acetone, methanol, carbon tetrachloride and toluene were taken from Ref.[C.1] while those for distilled water from Ref.[C.2] The liquid properties listed correspond to the present experimental conditions.

References for Appendix C

- C.1 Gallant, R.W., PHYSICAL PROPERTIES OF HYDROCARBONS, Vol. 1 and Vol. 2, Gulf Publishing Co. (1974).
- C.2 HANDBOOK OF CHEMISTRY AND PHYSICAL, 62nd Edition, CRC Press (1981-1982).

Liquid	Temp. °C	Density gm/cc	Surface Tension dynes/cm	Boiling Point at Atmospheric Pressure °C
Acetone	24.4	0.78	22.8	56.0
Methanol	23.3	0.79	22.3	65.0
	25.6	0.79	22.3	
Carbon Tetrachloride	31.3	1.58	25.4	77.0
Distilled Water	25.0	1.00	72.0	100.0
	50.0	0.99	67.9	
Toluene	20.0	0.87	28.4	111.0
	35.6	0.86	26.6	

Table C.1 Physical Properties of the Experimental Liquids.

APPENDIX D

CALCULATION OF BUBBLE VOLUME

The volume of a bubble (at any instant during formation) was determined from the frames of high-speed motion pictures and was based on the calculation method of L'Ecuyer and Murthy[D.1]. A description of the procedure is as follows:

1. The picture frame with the rod image whose actual diameter was known was projected on a screen equipped with a digital X-Y reader.
2. The scale of the digital X-Y reader was adjusted to the actual diameter of the rod corresponding to the diameter of the projected image. This would give the scale factor with a 1:1 ratio.
3. A picture frame of the same film from which the bubble volume was to be calculated was then projected on the screen.
4. The enlarged outline of the bubble image was divided into a series of truncated cones by means of horizontal lines. Figure D.1 illustrates one such outline. The volume of a bubble was then computed from the following equation:

$$V = \frac{\pi}{3} H_1^2 (3R_1 - H_1) + \sum_{i=1}^{n-1} \frac{\pi}{12} H_2 (d_i^2 + d_{i+1}^2 + d_i d_{i+1}) \quad D.1$$

$$+ \frac{\pi}{12} H_3 (d_n^2 + d_{n+1}^2 + d_n d_{n+1})$$

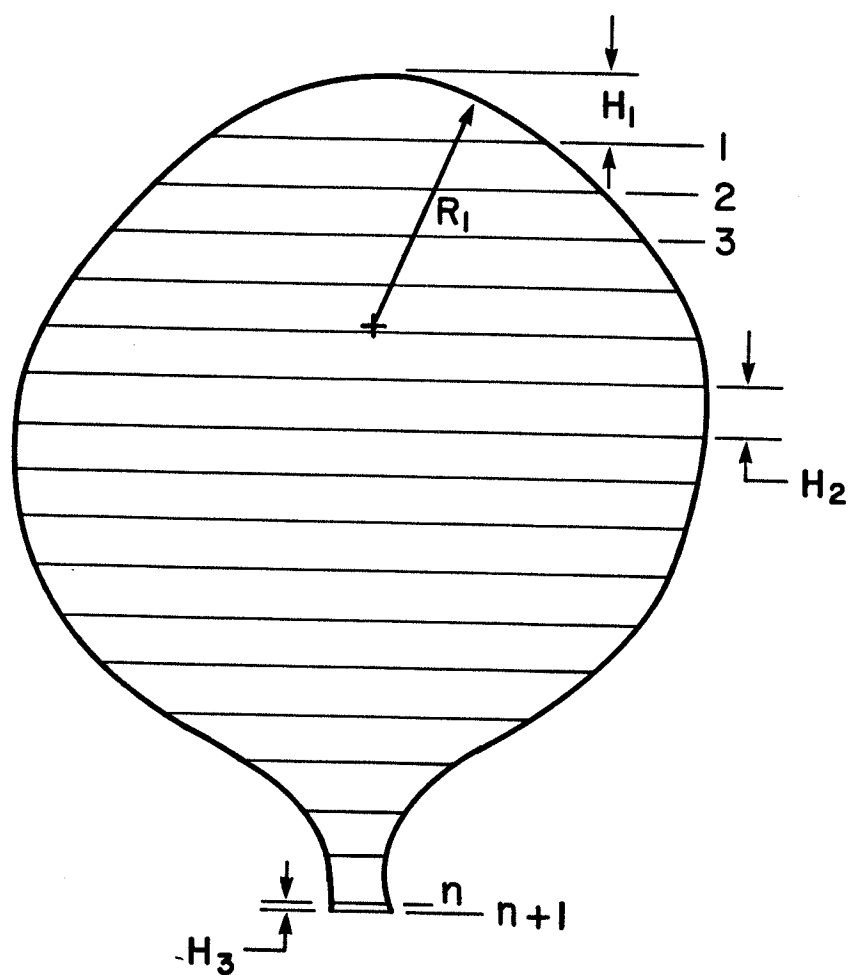


Fig. D.1 Enlarged Bubble Outline for Volume Calculation.

5. The true bubble volume was directly calculated with the measured values from Eqn. D.1 using a programmable calculator.

Reference for Appendix D

- D.1 L'Ecuyer, M.R. and S.N.B. Murthy, Energy transfer from a liquid to gas bubbles forming at a submerged orifice, NASA Report TND-2547 (1965).

APPENDIX E

CALCULATION OF ACTUAL FLOW RATE AT ORIFICE

Before attempting to determine the actual flow rate (liquid vapor + air) at the orifice, two corrections for air flow rates have to be made, i.e., the indicated air flow rate obtained from the calibration curve is first converted from standard conditions (14.7 psia and 70°F, or 76 cm Hg and 21.1°C) to metering conditions; next, the air flow rate at metering conditions is converted to the bubbling conditions immediately downstream of the orifice.

The indicated air flow rate can be corrected using Eqn. B.3 given in Appendix B. Equation B.3, rearranged and expressed in S.I. unit, is

$$Q_m = Q_I \sqrt{\frac{1.0 \times 76.0 \times T_m}{S.G. \times P_m \times (21.1 + 273.2)}} \quad E.1$$

where Q_m = Air flow rate at metering conditions

Q_I = Indicated air flow rate at standard conditions, (76 cm Hg and (21.1 + 273.2) K),

T_m = Temperature at metering conditions,

P_m = Pressure at metering conditions.

Assuming air as an ideal gas, the air flow rate at metering conditions is then corrected to the bubbling conditions using the ideal gas law which is given by

$$\frac{Q_m P_m}{T_m} = \frac{Q_b P_b}{T_b} \quad E.2$$

where Q_b is the air flow rate at the orifice, T_b is the

temperature of the pool, and P_b is the pressure in the plane of the orifice. Finally, the actual flow rate at the orifice was determined by Eqn. B.1 presented in Appendix B assuming both air and liquid vapor behave as ideal gases. With some changes in symbols, Eqn. B.1 is rewritten as follows:

$$\frac{Q_{\text{vap}}}{Q_{\text{mix}}} = \frac{Q_{\text{vap}}}{Q_b + Q_{\text{vap}}} = \frac{P_{\text{vap}}}{P_{\text{tot}}} \quad \text{E.3}$$

where Q_{vap} , Q_b , and Q_{mix} are the volumetric flow rates of liquid vapor, air and mixture respectively. P_{vap} is the partial pressure of the liquid vapor and P_{tot} is the total pressure of the mixture. P_{tot} is also equal to the pressure of P_b which is the sum of liquid head above the orifice and the atmospheric pressure.

Example (acetone)

Indicated air flow rate, Q_I	= 11.0 cm ³ /sec
Temperature at metering conditions, T_m	= 24.4°C
Pressure at metering conditions, P_m (gauge)	= 3.6 cm Hg
Temperature of pool liquid, T_b	= 24.4°C
$P_{\text{tot}} = P_b$ at orifice, $\frac{(12.0 \times 0.79)}{13.6} + 76.0$	= 76.7 cm Hg
P_{vap} , liquid vapor pressure at 24.4 C	= 22.2 cm Hg
S.G. of air	= 1.0

Substituting the values of Q_I , T_m , and P_m in Eqn. E.1, we have

$$Q_m = 11.0 \sqrt{\frac{1.0 \times 76.0 \times (24.4 + 273.2)}{1.0 \times (3.6 + 76.0) \times (21.1 + 273.2)}} \\ = 10.8 \text{ cm}^3/\text{sec}$$

Then the air flow rate at bubbling conditions (or orifice conditions) is calculated from Eqn. E.2. Thus,

$$Q_b = 10.8 \times \frac{(3.6 + 76.0) \times (24.4 + 273.2)}{76.7 \times (24.4 + 273.2)} \\ = 11.2 \text{ cm}^3/\text{sec}$$

Finally, the values of Q_b , P_{vap} , and P_{tot} are substituted in Eqn. E.3 to solve for the actual flow rate (liquid vapor + air) at the orifice:

$$\frac{Q_{\text{vap}}}{Q_{\text{mix}}} = \frac{Q_{\text{vap}}}{11.2 + Q_{\text{vap}}} = \frac{22.2}{76.7} = 0.289$$

Therefore,

$$Q_{\text{vap}} = 0.289 \times Q_{\text{vap}} + 11.2 \times 0.289 \\ = 4.6 \text{ cm}^3/\text{sec}$$

Thus, the actual flow rate at orifice is

$$Q_{\text{act}} = Q_{\text{mix}} = Q_{\text{vap}} + Q_b \\ = 4.6 + 11.2 \\ = \underline{15.8} \text{ cm}^3/\text{sec}$$

Table E.1 summarizes the calculation results of the actual flow rates for all liquids and the corresponding experimental conditions. The liquid vapor pressures were obtained from Refs.[E.1,E.2].

Liquid	Orifice Dia. cm	T_m $^{\circ}\text{C}$	T_b $^{\circ}\text{C}$	P_m cm Hg	Q_I cm^3/sec	Q_m cm^3/sec	Q_b cm^3/sec	Q_{act} (vap. + air) cm^3/sec
Acetone	0.3	24.4	24.4	3.6	11.0	10.8	11.2	15.8
	0.3	24.4	24.4	5.2	24.0	23.4	24.7	34.8
Methanol	0.3	23.3	23.3	6.5	35.0	33.7	36.3	42.3
	0.4	25.6	25.6	11.6	44.4	41.7	47.6	56.3
Carbon Tetra- chloride	0.3	23.3	31.1	7.8	16.5	16.0	17.3	21.1
	0.3	23.3	31.1	10.3	29.3	28.0	31.2	37.9
Distilled Water	0.6	25.5	25.5	41.4	88.7	71.9	109.8	113.5
	0.6	23.2	50.0	56.9	111.5	84.6	159.5	180.1
Toluene	0.6	23.3	35.6	49.1	91.9	71.9	122.0	130.1

Table E.1 Calculation Results of the Actual Flow Rates for All Tested Liquids and Corresponding Experimental Conditions.

References for Appendix E

- E.1 Gallant, R.W., PHYSICAL PROPERTIES OF HYDROCARBONS,
Vol. 1 and 2, Gulf Publishing Co. (1974).
- E.2 Keenan, J.H., F.G. Keyes, P.G. Hill and J.G. Moore,
STEAM TABLES, Wiley (1969).

APPENDIX F

BUBBLE IDENTIFICATION AND TABULATED DATA

Each bubble analyzed is identified by a code in which the first number refers to the orifice diameter in millimetres. The second letter in the code refers to the name of the liquid tested. The third number is the indicated air flow rate which is given as cubic centimetre per second. Following the indicated air flow rate is a dash and then the picture frame number at which the bubble taken to be analyzed started to form at the orifice. The frame number for each film was set to zero when a completely blank frame was seen on the screen just before the bubble images appeared following the filming of the rod. Should this be required for later review, the frame number in the code serves as a means of locating the analyzed bubble in the film. The following example illustrates the application of the code. Let 3A11-597 be the identification of a bubble analyzed. The first number(3) refers to the orifice diameter of 3 mm; the letter(A) refers to the liquid as acetone; the second number(11) refers to the indicated air flow rate of $11.0 \text{ cm}^3/\text{sec}$ while the last number(597) is the frame number which gives the location of the start of the bubble formation.

The tabulated data for the bubble growth obtained during the experimental investigation are presented in Tables F.1 to F.9. Three "first bubbles" (see Sec. 5.1) were analyzed, generally at random, for each set of conditions.

Table F.1 Bubble Growth Data for Acetone(Actual Flow Rate,
15.8 cm³/sec).

Orifice diameter: 0.3 cm
 Liquid temperature: 24.4 °C
 Room temperature: 24.4 °C
 Liquid height above the orifice: 12.0 cm
 Indicated air flow rate: 11.0 cm³/sec

Bubble Identification No. 3A11-597
 (Time/frame, 4.167 x 10⁻⁴sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
597	0.0	2.15	0.080
601	1.7	24.40	0.180
610	5.4	80.63	0.268
620	9.6	153.35	0.332
630	13.8	226.24	0.378
640	17.9	278.26	0.405
650	20.9	328.41	0.428
670	30.4	463.25	0.480
679	34.2	545.70	0.507

Bubble Identification No. 3A11-1237
 (Time/frame, 4.348 x 10⁻⁴sec/frame)

1237	0.0	1.75	0.075
1238	0.4	5.38	0.109
1241	1.3	13.68	0.148
1244	2.6	37.80	0.208
1250	5.2	79.34	0.267
1259	9.1	142.48	0.324
1269	13.5	196.92	0.361
1279	17.8	261.75	0.397
1289	22.2	313.92	0.422
1299	26.5	385.06	0.451
1317	34.3	520.46	0.499
1328	39.1	554.17	0.510

Bubble Identification No. 3A11-1382
 (Time/frame, 4.545 x 10⁻⁴sec/frame)

1382	0.0	1.15	0.065
1385	4.4	8.52	0.120
1389	3.2	37.62	0.238
1397	6.8	88.86	0.277
1407	13.6	168.43	0.343
1419	16.8	248.43	0.390
1434	23.6	347.04	0.436
1444	28.2	434.90	0.470
1459	35.0	532.05	0.503

Table F.2 Bubble Growth Data for Acetone(Actual Flow Rate, 34.8 cm³/sec).

Orifice diameter: 0.3 cm
 Liquid temperature: 24.4 °C
 Room temperature: 24.4 °C
 Liquid height above the orifice: 12.0 cm
 Indicated air flow rate: 24.0 cm³/sec

Bubble Identification No. 3A24-481
 (Time/frame, 4.167 x 10⁻⁴ sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
481	0.0	5.58	0.110
483	0.8	32.57	0.198
486	2.1	94.35	0.282
492	4.6	197.82	0.361
499	7.5	305.82	0.418
507	11.0	410.51	0.461
516	14.6	549.14	0.508
526	18.8	670.42	0.543
536	22.9	799.73	0.576
546	27.1	950.29	0.610
556	31.3	1095.61	0.640
566	35.4	1247.66	0.668
571	37.5	1363.09	0.689

Bubble Identification No. 3A24-1111
 (Time/frame, 4.348 x 10⁻⁴ sec/frame)

1111	0.0	3.71	0.096
1113	0.9	21.90	0.174
1116	2.2	80.97	0.268
1120	3.9	172.73	0.345
1125	6.1	236.23	0.383
1131	8.7	356.67	0.440
1138	11.7	449.85	0.475
1147	15.7	571.08	0.515
1157	20.0	702.83	0.552
1167	24.3	838.83	0.585
1177	28.7	1005.98	0.622
1187	33.0	1174.83	0.655
1197	37.4	1342.34	0.684

Bubble Identification No. 3A24-1228
 (Time/frame, 4.545 x 10⁻⁴ sec/frame)

1228	0.0	6.37	0.115
1230	0.9	29.69	0.192
1233	2.3	103.91	0.292
1236	3.6	184.07	0.353
1239	5.0	204.28	0.365
1243	6.8	278.68	0.405

Table F.2 - Cont'd

1248	9.1	363.47	0.443
1254	11.8	449.81	0.475
1261	15.0	557.21	0.511
1268	18.2	656.33	0.539
1277	22.3	821.22	0.581
1287	26.8	978.73	0.616
1297	31.4	1105.50	0.641
1309	36.8	1315.49	0.680

Table F.3 Bubble Growth Data for Methanol(Actual Flow Rate, 42.3 cm³/sec).

Orifice diameter: 0.3 cm
 Liquid temperature: 23.3 °C
 Room temperature: 23.3 °C
 Liquid height above the orifice: 12.0 cm
 Indicated air flow rate: 35.0 cm³/sec

Bubble Identification No. 3M35-800
 (Time/frame, 4.167 x 10⁻⁴ sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
800	0.0	2.06	0.079
802	0.8	25.74	0.183
804	1.7	69.60	0.255
806	2.5	125.14	0.310
808	3.3	168.30	0.343
810	4.2	200.24	0.363
812	5.0	216.50	0.372
820	8.3	384.52	0.451
830	12.5	557.94	0.511
840	16.7	752.61	0.556
850	20.8	936.90	0.607
860	25.0	1129.50	0.625
870	29.1	1302.80	0.678
880	33.3	1528.30	0.715
891	37.9	1829.70	0.759

Bubble Identification No. 3M35-1749
 (Time/frame, 4.545 x 10⁻⁴ sec/frame)

1749	0.0	3.59	0.095
1754	2.3	90.17	0.278
1757	3.6	186.43	0.354
1760	5.0	226.16	0.378
1763	6.3	314.85	0.422
1766	7.7	345.18	0.435
1769	9.1	401.38	0.458
1779	13.6	627.44	0.531
1789	18.2	802.42	0.578
1799	22.7	1067.16	0.634
1809	27.3	1210.00	0.662
1819	31.8	1305.80	0.678
1833	38.2	1837.24	0.760

Bubble Identification No. 3M35-2640
 (Time/frame, 4.545 x 10⁻⁴ sec/frame)

2640	0.0	1.56	0.072
2642	0.9	16.94	0.159
2644	1.8	66.21	0.251
2646	2.7	114.19	0.301

Table F.3 - Cont'd

2648	3.6	137.08	0.320
2650	4.5	165.63	0.341
2660	9.1	375.44	0.447
2670	13.6	627.66	0.531
2680	18.2	833.55	0.584
2690	22.7	1051.77	0.631
2700	27.3	1237.42	0.667
2710	31.8	1406.96	0.695
2720	36.4	1624.63	0.729
2731	41.4	1747.86	0.747

Table F.4 Bubble Growth Data for Methanol (Actual Flow Rate, 56.3 cm³/sec).

Orifice diameter:	0.4 cm
Liquid temperature:	25.6 °C
Room temperature:	25.6 °C
Liquid height above the orifice:	12.0 cm
Indicated air flow rate:	44.4 cm ³ /sec

Bubble Identification No. 4M44.4-452
(Time/frame, 4.167 x 10⁻⁴ sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
452	0.0	7.24	0.120
454	0.8	38.30	0.209
457	2.1	138.64	0.315
460	3.3	218.78	0.374
464	5.0	270.59	0.401
470	7.5	414.78	0.463
476	10.0	562.84	0.512
486	14.2	800.21	0.576
496	18.3	969.14	0.614
506	22.5	1158.20	0.652
516	26.7	1420.87	0.697
526	30.8	1593.95	0.725
536	35.0	1772.59	0.751
546	39.2	2063.02	0.790
555	42.9	2203.81	0.807

Bubble Identification No. 4M44.4-1004
(Time/frame, 4.167 x 10⁻⁴ sec/frame)

1004	0.0	7.24	0.121
1006	0.8	32.18	0.197
1009	2.1	129.13	0.314
1014	4.2	256.87	0.394
1020	6.7	423.38	0.466
1027	9.6	555.11	0.510
1035	12.9	668.07	0.542
1044	16.7	887.42	0.594
1054	20.8	1026.64	0.626
1064	25.0	1265.63	0.671
1074	29.2	1464.59	0.705
1084	33.3	1686.55	0.738
1094	37.5	1958.82	0.776
1100	40.0	2047.48	0.788

Bubble Identification No. 4M44.4-2652
(Time/frame, 4.545 x 10⁻⁴ sec/frame)

2652	0.0	5.56	0.110
2654	0.9	42.39	0.216
2657	2.3	164.92	0.340

Table F.4 - Cont'd

2661	4.1	229.73	0.380
2666	6.4	389.18	0.453
2672	9.1	562.89	0.512
2679	12.3	744.83	0.562
2687	15.9	942.00	0.608
2706	20.0	1242.25	0.667
2716	24.5	1457.90	0.703
2726	33.6	1940.80	0.751
2736	38.2	2152.90	0.801
2743	41.4	2228.90	0.810

Table F.5 Bubble Growth Data for Carbon Tetrachloride (Actual Flow Rate, $21.1 \text{ cm}^3/\text{sec}$).

Orifice diameter: 0.3 cm
 Liquid temperature: 31.1°C
 Room temperature: 23.3°C
 Liquid height above the orifice: 12.0 cm
 Indicated air flow rate: $16.5 \text{ cm}^3/\text{sec}$

Bubble Identification No. 3C16.5-1829
 (Time/frame, $5.000 \times 10^{-4} \text{ sec/frame}$)

Frame No.	Time, t ms	Bubble Volume $\text{cm}^3 \times 10^{-3}$	Bubble Equiv. Radius cm
1829	0.0	1.84	0.760
1831	1.0	17.94	0.160
1834	2.5	60.89	0.240
1838	4.5	99.95	0.290
1843	7.0	183.91	0.350
1849	10.0	257.41	0.400
1856	13.5	331.84	0.430
1864	17.5	419.76	0.460
1873	22.0	492.80	0.490
1883	27.0	622.53	0.530
1893	32.0	801.21	0.580
1903	37.0	930.34	0.610

Bubble Identification No. 3C16.5-1931
 (Time/frame, $5.263 \times 10^{-4} \text{ sec/frame}$)

1931	0.0	3.60	0.095
1933	1.1	24.60	0.180
1937	3.2	93.64	0.280
1942	5.8	145.41	0.330
1948	9.0	217.32	0.370
1956	13.2	321.47	0.430
1965	17.9	402.88	0.460
1975	23.2	513.92	0.500
1985	28.4	676.16	0.540
1995	33.7	820.02	0.580
2003	37.9	927.11	0.600

Bubble Identification No. 3C16.5-2033
 (Time/frame, $4.878 \times 10^{-4} \text{ sec/frame}$)

2033	0.0	5.58	0.110
2036	1.5	31.90	0.200
2039	2.9	67.32	0.250
2043	4.9	102.47	0.290
2048	7.3	172.40	0.350
2054	10.2	248.26	0.390
2061	13.7	317.91	0.420
2069	17.6	391.94	0.450
2078	22.0	472.31	0.480

Table F.5 - Cont'd

2088	26.8	576.02	0.520
2098	31.7	714.41	0.560
2110	37.3	841.65	0.590

Table F.6 Bubble Growth Data for Carbon Tetrachloride (Actual Flow Rate, 37.9 cm³/sec).

Orifice diameter:	0.3 cm
Liquid temperature:	23.3 °C
Room temperature:	23.3 °C
Liquid height above the orifice:	12.0 cm
Indicated air flow rate:	29.3 cm ³ /sec

Bubble Identification No. 3C29.3-1945
(Time/frame, 5.000 x 10⁻⁴ sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
1945	0.0	6.89	0.118
1947	1.0	35.55	0.204
1950	2.5	112.25	0.299
1953	4.0	163.08	0.339
1957	6.0	237.69	0.384
1962	8.5	341.76	0.434
1969	12.0	474.10	0.484
1977	16.0	617.82	0.528
1987	21.0	766.42	0.568
1997	26.0	930.94	0.606
2007	31.0	1070.27	0.635
2017	36.0	1276.08	0.673
2022	38.5	1356.85	0.687

Bubble Identification No. 3C29.3-2558
(Time/frame, 4.762 x 10⁻⁴ sec/frame)

2558	0.0	2.23	0.081
2560	1.0	17.63	0.162
2564	2.9	86.26	0.274
2568	4.8	149.02	0.329
2574	7.6	294.44	0.413
2581	11.0	385.18	0.451
2589	14.8	533.83	0.503
2598	19.0	665.88	0.542
2608	23.8	856.78	0.589
2618	28.6	985.05	0.617
2628	33.3	1257.71	0.670

Bubble Identification No. 3C29.3-2841
(Time/frame, 4.762 x 10⁻⁴ sec/frame)

2839	0.0	6.37	0.115
2843	1.0	39.53	0.211
2846	2.4	86.04	0.274
2851	4.8	177.72	0.349
2856	7.1	259.45	0.396
2862	10.0	351.72	0.438
2870	13.8	479.46	0.486
2879	18.1	608.92	0.526

Table F.6 - Cont'd

2889	22.9	746.57	0.563
2900	28.1	898.75	0.599
2910	32.9	1052.51	0.631
2919	37.1	1190.61	0.657

Table F.7 Bubble Growth Data for Distilled Water (Actual Flow Rate, 113.5 cm³/sec).

Orifice diameter:	0.6 cm
Liquid temperature:	25.5 °C
Room temperature:	25.5 °C
Liquid height above the orifice:	12.0 cm
Indicated air flow rate:	88.7 cm ³ /sec

Bubble Identification No. 6W88.7-1404
(Time/frame, 4.545 x 10⁻⁴sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
1404	0.0	7.24	0.120
1406	1.0	177.83	0.350
1408	1.8	370.32	0.445
1411	3.2	434.88	0.470
1415	5.0	632.52	0.530
1420	7.3	909.09	0.600
1427	10.5	1275.05	0.670
1436	14.5	1687.80	0.740
1446	19.1	2218.67	0.810
1456	23.6	2620.43	0.860
1466	28.2	3131.87	0.910
1476	32.7	3558.42	0.950
1487	37.7	4092.22	0.990
1497	42.3	4614.34	1.030
1513	49.5	5400.61	1.090
1526	55.5	6069.07	1.130

Bubble Identification No. 6W88.7-1729
(time/frame, 5.000 x 10⁻⁴sec/frame)

1729	0.0	10.31	0.135
1731	1.0	122.35	0.308
1735	3.0	447.56	0.475
1739	5.0	620.85	0.529
1745	8.0	1008.56	0.622
1753	12.0	1488.56	0.708
1763	17.0	2041.62	0.787
1773	22.0	2653.14	0.859
1783	27.0	3304.70	0.924
1793	32.0	3900.81	0.977
1803	37.0	4613.29	1.033
1813	42.0	5381.48	1.087
1823	47.0	6170.04	1.138
1841	56.0	7028.56	1.188

Bubble Identification No. 6W88.7-2611
(Time/frame, 4.762 x 10⁻⁴sec/frame)

2611	0.0	5.89	0.112
2615	1.9	254.25	0.393

Table F.7 -Cont'd

2620	4.3	877.91	0.594
2638	12.9	1499.21	0.710
2648	17.6	2177.00	0.804
2660	23.3	2806.16	0.875
2675	30.5	3764.18	0.965
2690	37.6	4484.52	1.023
2710	47.1	5605.75	1.102
2720	51.9	6777.85	1.174

Table F.8 Bubble Growth Data for Distilled Water (Actual Flow Rate, 180.1 cm³/sec).

Orifice diameter: 0.6 cm
 Liquid temperature: 50.0 °C
 Room temperature: 23.2 °C
 Liquid height above the orifice: 12.0 cm
 Indicated air flow rate: 111.5 cm³/sec

Bubble Identification No. 6W111.5-1833
 (Time/frame, 5.000 x 10⁻⁴ sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
1833	0.0	13.06	0.146
1835	1.0	294.52	0.413
1837	2.0	638.35	0.534
1841	4.0	973.98	0.615
1848	7.5	1730.76	0.745
1858	12.5	2628.73	0.856
1868	17.5	3436.11	0.936
1878	22.5	4251.94	1.005
1888	27.5	5191.85	1.074
1898	32.5	6124.98	1.135
1908	37.5	6857.08	1.179
1918	42.5	7721.95	1.226
1928	47.5	8330.53	1.256
1947	57.0	10331.15	1.351

Bubble Identification No. 6W111.5-1994
 (Time/frame, 4.651 x 10⁻⁴ sec/frame)

1994	0.0	15.91	0.156
1996	0.9	260.25	0.396
2000	2.8	690.81	0.548
2006	5.6	1252.20	0.669
2014	9.3	1873.35	0.765
2024	14.0	2790.46	0.873
2034	18.6	3640.83	0.954
2044	23.3	4454.33	1.021
2059	30.2	5745.28	1.111
2074	37.2	7164.37	1.196
2086	42.8	8444.12	1.263
2104	51.2	10357.98	1.352

Bubble Identification No. 6W111.5-2300
 (Time/frame, 4.762 x 10⁻⁴ sec/frame)

2300	0.0	11.74	0.141
2302	1.0	104.80	0.292
2304	1.9	314.81	0.422
2308	3.8	713.21	0.554
2315	7.1	1297.29	0.677
2323	11.0	2059.53	0.789

Table F.8 - Cont'd

2333	15.7	2833.20	0.878
2343	20.0	3640.06	0.954
2353	25.2	4690.07	1.038
2363	30.0	5668.39	1.106
2378	37.1	7158.07	1.196
2396	45.7	8346.51	1.258
2401	48.1	8863.49	1.283

Table F.9 Bubble Growth Data for Toluene (Actual Flow Rate, 130.1 cm³/sec).

Orifice diameter:	0.6 cm
Liquid temperature:	35.6 °C
Room temperature:	23.3 °C
Liquid height above the orifice:	12.0 cm
Indicated air flow rate:	91.9 cm ³ /sec

Bubble Identification No. 6T91.9-293
(Time/frame, 4.255×10^{-4} sec/frame)

Frame No.	Time, t ms	Bubble Volume cm ³ x 10 ⁻³	Bubble Equiv. Radius cm
293	0.0	8.18	0.125
296	1.3	177.84	0.348
300	3.0	493.41	0.490
305	5.1	776.75	0.570
314	9.0	1356.55	0.687
324	13.2	1961.48	0.777
334	17.4	2541.19	0.847
344	21.7	2886.72	0.883
354	26.0	3844.16	0.972
364	30.2	4412.02	1.017
374	34.5	5103.46	1.068
389	40.9	6084.20	1.132
404	47.2	7105.02	1.193
422	54.9	8147.77	1.248

Bubble Identification No. 6T91.9-2461
(Time/frame, 4.651×10^{-4} sec/frame)

2461	0.0	6.37	0.115
2463	0.9	137.26	0.320
2465	1.9	346.30	0.436
2470	4.2	733.09	0.559
2478	7.9	1230.62	0.665
2488	12.6	1922.92	0.771
2498	17.2	2741.09	0.868
2513	24.2	3323.77	0.926
2530	32.1	4478.63	1.023
2545	39.1	5580.15	1.103
2560	46.1	6629.09	1.165
2578	54.4	8508.17	1.266

Bubble Identification No. 6T91.9-2694
(Time/frame, 4.651×10^{-4} sec/frame)

2694	0.0	9.20	0.130
2700	2.8	365.84	0.444
2705	5.1	704.06	0.552
2708	6.5	927.45	0.605
2719	11.6	1544.77	0.717
2729	16.3	2181.71	0.805

Table F.9 - Cont'd

2739	20.9	2701.65	0.864
2749	25.6	3371.89	0.930
2759	30.2	4026.07	0.987
2774	37.2	5137.21	1.070
2790	44.7	6104.53	1.134
2804	51.2	7290.47	1.203
2814	55.8	8482.92	1.265