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Argonne National Laboratory

DEVELOPMENT OF A FLUOROSCOPE FOR STUDYING TWO-PHASE FLOW PATTERNS

by

John Johanns

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DEVELOPMENT OF A FLUOROSCOPE FOR
STUDYING TWO-PHASE FLOW PATTERNS

by

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and
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NOMENCLATURE ➞

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>	<u>Units</u>	<u>Symbol</u>	<u>Description</u>	<u>Units</u>
A	Cross-sectional area of the flow channel	ft ²	g	Acceleration of gravity	ft/sec ²
ΔA	Area of a resolution element	cm ²	h	Planck's constant	erg sec
B	Brightness	arbitrary	i	Electron current	Amp
C	Contrast	dimensionless	ℓ	Measure of resolution	/cm
D	Inner diameter of the pipe	ft	n	Number of electrons on focal spot	/sec
E	Energy of an X-ray photon	erg	p	Distance	cm
F	Quantum flux, as defined in Eq. (8)	cm ² /sec	q	Distance	cm
I	Intensity	erg	r	Radius of the pipe, variable	cm
I_λ	Spectral intensity	erg/cm ² /sec	s	Size focal spot	cm
I_0	Number of photons	cm ² /sec	Δt	Integration time	sec
M	Magnification	dimensionless	δ	Length of pipe material traversed by X-ray beam	cm
P	Pressure	psi	δ_p	Length of phosphor traversed by X-ray beam	cm
Q_f	Volumetric flow rate of the liquid	ft ³ /sec	ϵ	Efficiency	dimensionless
Q_g	Volumetric flow rate of the gas	ft ³ /sec	λ	Wavelength	cm
V	Voltage	Volt	λ_0	Wavelength, Duane-Hunt limit	cm
V_0	Voltage corresponding to Duane-Hunt limit	Volt	μ_f	Absorption coefficient of the fluid	/cm
W_f	Mass flow rate of the liquid	lb/sec	μ_g	Absorption coefficient of the phosphor	/cm
W_g	Mass flow rate of the gas	lb/sec	μ_w	Absorption coefficient of the pipe wall material	/cm
Z	Atomic number	-	μ_p	Absorption coefficient of the phosphor	/cm
c	Velocity of light	cm/sec	σ	Signal	arbitrary
d	Length of fluid traversed by X-ray beam	cm	ν	Frequency	sec
d_s	Diameter of a resolution element	cm			
Δd	Length of gas traversed by X-ray beam	cm			

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I. INTRODUCTION

The simultaneous flow of gas and liquid takes place in a number of different configurations or flow patterns. The flow pattern that will exist is determined by factors such as the flow rate of each phase, the dimensions and orientation of the flow channel, the distance from the channel inlet, and the physical properties of the fluid, namely, the density, viscosity, and surface tension.⁽¹⁻⁶⁾

Two-phase flow parameters of pressure drop, void fraction, average density, and heat transfer coefficient have all been found to be dependent upon the flow pattern.^(1,3,4,5,7) For establishing a particular flow pattern, certain of the aforementioned parameters dominate; their relative importance varies with the various flow configurations.⁽⁸⁾ It would seem, therefore, that correlations for predicting pressure drop, void fraction, heat transfer coefficient, etc., can more readily be developed for a specific flow pattern, since many of the variables can be eliminated. Several such correlations for specific flow patterns are already in existence or under development.⁽⁹⁻¹¹⁾

The use of these correlations, on the other hand, is only possible if the boundaries of the flow patterns are known. Figure 1 shows a proposed flow map.⁽¹⁰⁾ Construction of such maps are generally accomplished by visual observations of the flow patterns in a transparent pipe.⁽¹⁾ This method is generally restricted to low pressures because of the low strength of such pipes unless special elaborate test sections are designed. Radford and Dunn have used pressure drop observations as the basis for their flow maps.⁽³⁾

Fig. 1

Flow Regime Map for a Vertical Pipe. I. Bubble Flow; II. Slug Flow; and III. Annular Flow.

Figure 2 shows a typical curve of unit pressure drop as a function of gas-liquid volume ratio and constant liquid flow rate. This curve was

Fig. 2. Unit Pressure Drop as Function of Gas-Liquid Volume Ratio and Constant Liquid Flow

divided into four regimes characterized by changing pressure gradients. The subdivisions into the various flow patterns were made through use of the visual observations and pressure drop measurements at low pressure as the basis of comparison. This last feature makes the extrapolation to higher pressures questionable.

Griffith has used a probe to measure the electrical resistance between the center of the pipe and the pipe wall to characterize the flow patterns.⁽¹²⁾ If the center of the pipe is filled with liquid, as is the case of passage of a liquid slug, the resistance has a certain finite value. Calibration is likewise done on the basis of comparison with observations made at low pressure.

It is clear that both methods use visual observations made at low pressure to interpret data at high pressure. No assurance can be given that this is a sound procedure. A new technique is needed which would enable one to observe flow patterns directly in high-pressure systems. Therefore, an investigation has been undertaken to establish the feasibility of observing two-phase flow patterns in high-pressure systems by means of a fluoroscopic system with X rays.

II. THEORETICAL CONSIDERATIONS

To accomplish flow observations with X rays, one must be able to penetrate the pipe walls and simultaneously observe density changes in the fluid with a high contrast. The pipe walls can be penetrated by using a sufficient number of high-energy photons which have a low attenuation in the structural materials. To observe density changes in the fluid, however, a high absorption in the fluid is needed. This requires a sufficient number of low-energy photons which have a high attenuation coefficient in the fluid. It is clear that there are conflicting requirements with regard to the energy of the photons, and a compromise is necessary. An analysis was therefore made with a fluoroscopic system to determine if such a compromise can be made. The fluoroscopic system, shown in Fig. 3, consists of an X-ray tube, collimator, image-intensifier tube, and the TV system. An analysis of each of the components follows.

Fig. 3

Schematic Diagram
of the Fluoroscope

The X-ray Tube

The working of the X-ray tube can be described as follows: Electrons, emitted by a heated filament and accelerated through a high electrical potential, impinge on a tungsten target (see Fig. 4). The position where the electrons hit the target is called the focal spot. There the electrons are deaccelerated and stopped. During this process a part of their energy is given off as X rays, which emerge from the focal spot with different energies and an energy spectrum is created, as illustrated in Fig. 5, which is a plot of the spectral intensity (I_λ) as a function of the wave length (λ) at constant voltage. The spectral intensity is defined as the total energy of all photons with a wavelength λ passing through 1 cm^2 in 1 sec. The spectrum can be divided in a continuous and a characteristic spectrum.

Fig. 4

The Production of X Rays

Fig. 5

A Typical X-ray Spectrum
Showing Characteristics and
Continuous Radiation

The characteristic spectrum is a line spectrum originating when an electron of an outer shell of the atom of the target material falls into a vacant orbit of an inner shell of the same atom. The vacancy is created if an electron from the filament knocks an orbital electron from its place. The energy of the emitted X ray is the difference between the energy of the electron in the outer shell and its energy in the inner shell:

$$E = h\nu = hc/\lambda, \quad (1)$$

where

E = energy of the X-ray photon, erg

h = Planck's constant = $6.6242 (10^{-27})$ erg-sec

ν = frequency of the X-ray, cps

c = velocity of light = $2.99776 (10^{10})$ cm/sec

λ = wavelength of the X ray, cm.

The wavelengths of the characteristic spectrum depend on the target material. Further, the characteristic radiation is emitted only if the voltage is high enough, since the electrons from the filament need a certain minimum energy to knock one of the orbital electrons from its position. For tungsten this threshold energy is 70 kV.

The intensity or total energy of a line in the characteristic spectrum can be given by the empirical relation⁽¹³⁾

$$I = C(V - V_0)^n; \quad (V < 4V_0), \quad (2)$$

in which C and n are constants to be determined experimentally, V is the tube voltage, and V_0 is the minimum excitation potential for a given element (the threshold energy). The constant n varies from 1.5 to 2.0.⁽¹⁴⁾

The continuous spectrum is caused by bremsstrahlung. The spectral intensity is given by the expression⁽¹⁴⁾

$$I_\lambda = 4.95 (10^{-50}) \frac{ncZ}{\lambda_0 \lambda} (\lambda - \lambda_0), \text{ ergs per cm}^2 \text{ per sec}, \quad (3)$$

in which n is the number of electrons per sec on the focal spot:

$$n = i/1.6 (10^{-19}), \quad (4)$$

and

i = the tube current, Amp

c = the velocity of light = $2.99776 (10^{10})$ cm/sec

Z = the atomic number of the target material

λ = the wavelength, cm

λ_0 = the minimum wavelength as defined by the tube voltage, cm.

The wavelength λ_0 is sometimes called the Duane-Hunt limit. From the origin of X-ray production it follows that the photon energy never can exceed the energy of an electron from the filament. By applying Eq. (1) and taking the energy equal to the energy of the electron, we obtain the following equation:

$$\lambda_0 = (hc/V) 6.25 (10^{11}), \text{ cm}, \quad (5)$$

where

h = Planck's constant = $6.6242 (10^{-27})$ erg/sec

c = the velocity of light = $2.99776 (10^{10})$ cm/sec

V = the tube voltage, V.

Integration of Eq. (3) over the whole spectrum gives the total intensity of the X-ray beam.⁽¹³⁾ The total energy is found to be proportional to the tube current (i) and the square of the voltage (V^2). Division of the total energy by the kinetic energy of the exciting electrons gives the efficiency (ϵ) of the X-ray tube for the continuous spectrum:⁽¹³⁾

$$\epsilon = 9.12 (10^{-10}) ZV, \quad (6)$$

where

Z = the atomic number of the target material

V = the voltage of the X-ray tube, V.

For 150 kV one obtains from Eq. (6) an efficiency of 1%. This means that the major part of the energy of the exiting electrons is dissipated as heat to the focal spot. A high intensity, which means high voltage and high tube current, will heat up the target enormously. For good cooling, it is advantageous to make the focal spot large, because the heat is spread out over a larger area. A large focal spot, on the other hand, causes the picture of an object to have blurred boundaries, as is illustrated in Fig. 6. A compromise has to be found. A tube capable of operating continuously at 150 kV and 6 mA and with a focal spot of 0.3 mm is possible.

The numerical density of photons of wavelength λ passing through 1 cm^2 in 1 sec is obtained by dividing I_λ of Eq. (3) or I of Eq. (2) by hc/λ , as seen in Eq. (1).

Fig. 6

Blurring as a Result
of the Finite Size of
the Focal Spot

The X-ray tube is supplied by the normal AC power supply which gives variable voltage to the tube. The tube only operates during the period in which the voltage is positive, because the anode has to be positive. This means that the voltage to the tube has to be rectified. Basically, this can be done in two different ways:

1. The voltage of the tube is zero during that half of the period in which the line voltage is negative. Half-wave rectification is the result, as is demonstrated in Fig. 7.

2. The polarity of the voltage is reversed as the voltage is negative. This results in full-wave rectification, as is shown in Fig. 8.

In point one, no X rays are produced during one-half of each period, but in point two the X rays are produced during the entire period.

Fig. 7

Half-wave Rectification

Fig. 8

Full-wave Rectification

The use of a gamma-ray source or a beta-excited X-ray source is not possible, because these sources emit too small a number of photons per sec as compared with the number emitted by an X-ray tube. The use of sources of higher energy diminishes the contrast. To obtain the number of photons that are required, the amount of radioactive material would have to be increased. This, in turn, would require a larger volume and thus a larger emitting surface or "focal spot."

The Collimator

The X-ray beam after passing through the pipe containing the two-phase mixture is of low intensity because of the high absorption in pipe

walls and fluids. On the other hand, that part of the X-ray beam which passes on both sides of the pipe is undisturbed and therefore of high intensity. If both are allowed to fall on a phosphor screen, a dark area appears on the screen, representing the pipe, and very bright areas appear on both sides of it. Because of the large difference in brightness, observation of brightness differences in the dark area, which is the one of importance, would be difficult to make if not impossible. This problem becomes even more severe if one looks at the phosphor with the help of a TV camera, which cannot accommodate large brightness differences.

It is therefore necessary to collimate the X-ray beam to such an extent so as to exclude any X rays from bypassing the pipe. The collimator consists of two lead fixtures with an aperture comparable with the pipe diameter, as shown in Fig. 9a.

The collimator consists of two lead fixtures with an aperture comparable with the pipe diameter, as shown in Fig. 9a. Because of scattering and breakup of the X-ray beam on the edges of the collimator, the aperture has to be smaller than the pipe diameter to obtain a complete dark background on the phosphor screen (see Fig. 9b). The effect becomes more severe if the source is close to the pipe. The smaller aperture causes a lower intensity on the outer portions of the pipe. This effect can be reduced by placing the collimator close to the pipe. Also, the remaining brighter parts on the phosphor screen can be removed by a second collimator placed behind the pipe close to the phosphor, as shown in Fig. 9c.

Fig. 9. The Collimator

It is not advisable to use only the second collimator because scattering will be greatly increased and also shielding against exposure of personnel becomes more difficult.

The Image-intensifier Tube

The high absorption in the pipe walls, usually made of stainless steel, and in the fluid, causes very low X-ray intensities after the penetration of the pipe. These intensities are too low to make a visible picture on a fluoroscopic screen. This problem can be alleviated by the use of an image-intensifier tube which accomplishes a brightness gain of at least 3000 and, therefore, allows detection of these very low intensities.

The workings⁽¹⁴⁾ of the image-intensifier tube (see Fig. 10) is described below, and two important factors that limit its effectiveness are discussed in detail.

A phosphorescent screen converts the information contained in the X-ray beam into a light image. The light photons then strike on a photocathode attached to the phosphor. The electrons from the photocathode are accelerated through a 33-kV electrical potential and are focused on a phosphor screen, the diameter of which is an order of magnitude smaller than the diameter of the first screen. The final image is formed on this screen.

Fig. 10. The Image-intensifier Tube

The first phosphor screen of the image-intensifier tube lights up when it absorbs X-ray photons. The brightness with which it will light up is proportional to the number of photons absorbed.* The brightness of two adjacent elements on the phosphor screen will differ if the beam that strikes the first element undergoes more absorption on its way through the pipe with the two-phase mixture than the beam that strikes the second adjacent element. There will be a contrast between the two elements. This contrast can be defined as

$$C = \frac{B_2 - B_1}{B_2}, \quad (7)$$

when

B_1 = the brightness of an element

B_2 = the brightness of the adjacent element

C = the contrast.

The production of X rays is a statistical process which means that the number of photons of given wavelength varies with time. If one considers the number of photons as the signal (σ), then the noise as caused by the statistical fluctuations can be represented by $\sigma^{1/2}$.

*The brightness is only a very weak function of the energy of the photons in the range of operation; therefore, this dependence is not considered.

If the signal-to-noise ratio, which is given by $\sigma^{1/2}$ is large, as in the case of a large quantum flux, then the fluctuations are not observed by the human eye. The quantum flux after passage through the pipe, however, is small, as explained earlier. Therefore the signal-to-noise ratio will be small. As a result, "a resolution element can be perceived at a minimum contrast only."⁽¹⁵⁾ This minimum perceptible contrast can be given by the relation⁽¹⁶⁾

$$C_{\min} = \frac{k}{\sqrt{F(\Delta A)(\Delta t)}}, \quad (8)$$

where

$C_{\min}$ = the minimum perceptible contrast

k = constant which varies between 3 and 5 depending upon the observer⁽¹⁵⁾

ΔA = the area of a resolution element, cm^2 ; if d_s is the diameter in cm of this resolution element, then ΔA is equal to $(\pi/4)d_s^2$.

Δt = the integration time, sec; the integration time of the human eye is about 0.2 sec. The integration time decreases to 0.16 sec if TV viewing is used because between two frames no information is sent to the human eye.

F = the minimum quantum flux found in the system, $\text{no.}/\text{cm}^2/\text{sec}$.

Figure 11 illustrates how the minimum quantum flux is determined by a plot of the number of quanta found in each stage of the system. Stage 1 presents the number of quanta emitted by the source in the direction of the object. Stage 2 presents the number of quanta left after passage through the object. Stage 3 presents the number of quanta absorbed by the first phosphor screen. Stage 4 presents the number of light photons emitted by the first phosphor screen. Stage 5 presents the number of electrons emitted by the photocathode. Stage 6 presents the number of electrons impinging on the second phosphor. Stage 7 presents the number of light photons

Fig. 11

Graphic Representation of the Photon Intensities in Different Stages of the Fluoroscope

emitted by the second phosphor. Stage 8 presents the number of photons absorbed by the eye, and the number of electrons emitted by the photocathode of a TV camera in the case of TV viewing. For eye viewing, F will be the quantum flux found in Stage 8. For TV viewing, F will be the quantum flux found in Stage 3. This last quantum flux is usually found to be higher than the one in Stage 8.

To estimate the performance of the image tube, the values of C , in Eq. (7) and of F , in Eq. (8) have to be evaluated. As pointed out before, the contrast is the result of the difference in quantum flux on two adjacent elements on the phosphor screen. Therefore, this contrast is dependent upon the difference in the amount of absorption in two corresponding elements in the object. If $I_0(\lambda)$ is the number of photons of wavelength λ per cm^2 per sec incident on the object and an exponential decrease is assumed (see Fig. 12), then the contrast can be given by

$$C = 1 - \frac{\int_{\lambda_0}^{\infty} I_0(\lambda) \exp - [\mu_w(\lambda)\delta + \mu_f(\lambda)d] d\lambda}{\int_{\lambda_0}^{\infty} I_0(\lambda) \exp - [\mu_w(\lambda)\delta + \mu_f(\lambda)(d - \Delta d) + \mu_g(\lambda)\Delta d] d\lambda}, \quad (9)$$

in which

μ_w = the absorption coefficient of the wall material of the pipe, per cm

μ_f = the absorption coefficient of the fluid, per cm

μ_g = the absorption coefficient of the gas or vapor, per cm

δ = the length of pipe material traversed by the X-ray beam, cm

d = the length of fluid traversed by the X-ray beam, cm

Δd = the length of gas or vapor traversed by the X-ray beam, cm

λ = the wavelength, cm.

The integration has to be carried out over the whole X-ray spectrum. Thus the limits are from the Duane-Hunt limit (λ_0) to infinity. As has been

Fig. 12

Schematic Representation of
X-ray Penetration through
Different Layers of Material

mentioned previously, with TV viewing or with large brightness intensification, the first phosphor screen will most probably be the place with the lowest quantum flux. By assuming that this will be the case in the system under study, one obtains the following relation for F :

$$F = \int_{\lambda_0}^{\infty} I_0(\lambda) \exp - \left[\mu_w(\lambda) \delta + \mu_f(\lambda)(d - \Delta d) + \mu_g(\lambda) \Delta d \right] \left[1 - \exp - \mu_p(\lambda) \delta_p \right] d\lambda. \quad (10)$$

The performance of the system is determined by the quantum noise and is completely described by the Eqs. (8), (9), and (10).

The integrations are difficult to carry out. For some applications, however, it is sufficient to assume that the average photon energy is about $2/3$ of the tube voltage.⁽¹³⁾ From Eqs. (8), (9), and (10) and from Fig. 11, it can be seen that TV viewing has an advantage because the minimum number of quanta, F , will then be found in an earlier stage and also will be larger than without TV viewing. The performance of the system then can be improved by raising the quantum flux (by increasing the source strength) or by lowering the absorption in the pipe walls, or both.

The TV System

The advantage of TV viewing instead of eye viewing was explained in the previous section. In addition, radiation which tends to limit accessibility makes remote viewing very desirable. Before discussing the TV viewing system in detail, a definition of resolution is given: resolution is "the ability of an image reproducing system to represent the fine structure of an object."⁽¹⁷⁾

In photography the resolution is measured by the number of black and white lines which can be observed in a certain space. One black and one white line is counted as one line. In television the resolution is measured by counting the black and white lines separately. In addition to this, in television one has to discriminate between vertical and horizontal resolution: the vertical resolution is determined by the number of scanning lines; the horizontal resolution can be described by the ability of the system to reproduce a vertical line, as determined by the bandwidth of the system. The resolution needed for the TV system in a fluoroscopic system is determined by the resolution performance of the rest of the fluoroscope. The resolution performance of the image-intensifier tube is about 420 lines/in. on the output screen. This corresponds to 840 TV lines. This, then, is the minimum number of scanning lines needed to avoid loss of resolution.

In order to choose the right kind of TV system, two different kinds of cameras should be considered - the orthicon and the vidicon. Figure 13 presents a schematic diagram of the orthicon. Light from the picture to be

televised falls on a photocathode. The electrons from this photocathode are focused on and accelerated towards a target. There they give rise to secondary electrons which are collected by the collector mesh. The result is a pattern of positive charges on the target. The target is scanned by an electron beam. The spots with the positive charges are neutralized by electrons from the beam. The rest of the electrons are returned to a multistage electron multiplier which finally provides the output signal.

Fig. 13
The Orthicon

The vidicon is illustrated in Fig. 14. Light from the picture to be televised passes through a transparent conductive film, called the signal plate, and falls on a photoconductive layer. The signal plate is charged to a positive potential and the photoconductive layer is floating. The two layers may be considered as two plates forming a capacitor with a dielectric resistance which varies with changing light. The resistance of the lighter areas on the photoconductive layer is lowered in proportion to the intensity of the light. This causes electrons to flow to the transparent film, and there results a pattern of positive charges on the photoconductive layer. An electron beam scans this pattern. More electrons from the beam pass through the areas with positive charge on the photoconductor to the signal plate and there add to the output signal.

Fig. 14
The Vidicon

The orthicon is more sensitive than the vidicon. The orthicon can operate at light levels as low as 10^{-4} ft-Lamberts. The vidicon needs 4 ft-Lamberts for good operation. The orthicon also gives less smear when scanning moving objects. The orthicon, however, is much more complex, more difficult to operate, and much more costly. Both systems, however, have the required minimum resolution as discussed previously. Wilson⁽¹⁸⁾ has derived an equation for the number of light photons emitted by the output phosphor of the image-intensifier tube. This can be compared with the minimum light level necessary to operate the TV camera. The equation, however, is very difficult to evaluate because many of the factors in this equation are unknown.

Because of the expected low light levels on the output screen of the image-intensifier tube and because of the presence of moving objects, the orthicon would be preferred. However, the vidicon can be used successfully.

The Object

The object in this study consists of a conduit with a two-phase mixture flowing inside. The goal to be reached is: to perceive voids in the liquid with a contrast as high as possible. This contrast is dependent on properties of the fluid, on the conduit material, and on the conduit geometry.

From the discussion presented on the image-intensifier tube it follows that the absorption in the fluid has to be high in order to obtain a high contrast. For monoenergetic photons, Eq. (9) simplifies to

$$C = 1 - \exp(-(\mu_f - \mu_g)\Delta d). \quad (11)$$

Thus, C is high if: (1) μ_f is large, (2) μ_g is small, and (3) Δd is large. Curves of the absorption coefficient of water show that for photon energies between 50 and 200 kV, the absorption coefficient does not decrease substantially. For energies lower than 50 kV, however, a large increase in absorption coefficient is obtained if the photon energy is decreased. Therefore, operation with photon energies below 50 kV is recommended for a high contrast.

The absorption coefficient μ_g is influenced by the pressure of the system, because μ_g is proportional to the density and therefore dependent upon the pressure. This is, of course, also true for the fluid, but the influence of the pressure is of much less importance. Figure 15 illustrates this with a plot of the contrast obtained with a water vapor bubble with diameter Δd as a function of the pressure for 100-kV photons. After an initial steep drop, the contrast decreases slowly with increasing pressure until in the vicinity of the critical pressure again a steep drop occurs. The figure also shows that for larger Δd , the contrast decreases faster with pressure. Because the distance traveled by the X-ray photon through

Fig. 15

Contrast as Function of Pressure and Bubble Size, Computed for 100-kV X-ray Photons

the bubble is not constant, but varies with the radius of the bubble, the contrast will also vary with radius. Therefore, the boundaries will never be sharp. The amount of "shadow" inside the bubble can be computed with the use of Eq. (9).

Because a minimum quantum flux is needed to perceive an object with low contrast, the absorption in the pipe walls has to be below a certain value. Therefore, μ_w and δ have to be small. Figure 16 shows the computed absorption in steel as a function of the energy and constant δ . ($\delta = 0.675$ cm obtained from a 1-in. Schedule 40 pipe.) For comparison purposes the absorption in a 2-cm layer of water is also shown. Below a photon energy of 90 kV, the absorption in the wall is almost complete if $\delta = 0.675$ cm. A smaller value of δ improves the penetration, but operation below 50 kV is not feasible. It should be noted that a smaller value of δ also leads to a decrease of scattering and therefore improves the picture quality.

Fig. 16

The Absorption of X-ray Photons in Different Layers of Steel as Function of Photon Energy

Figure 17 presents similar information for titanium. Operation with much lower photon energies is now feasible, but only a very thin

Fig. 17

The Absorption of X-ray Photons in Different Layers of Titanium as Function of Photon Energy

pipe allows operation below 50 kV. However, the minimum quantum flux will be increased if titanium is used as the conduit material, and lower contrasts can be perceived.

Fig. 18: The Absorption of X-ray Photons in Aluminum

An absorption curve for aluminum is given in Fig. 18. As can be seen, operation with energy levels below 50 kV is possible. The strength of aluminum conduits, however, is not sufficient to withstand high pressures. Special alloys can alleviate this, but other factors (like corrosion resistance, weldability, and availability) influence their usefulness.

The geometry can either be round or rectangular. In the case of a round pipe, the thickness δ varies with the radius of the pipe, as is shown in Fig. 19a. This has an important influence on the results. In Fig. 19b, the absorption in the wall

is presented as a function of the radius for a photon energy of 100 kV. Two curves for steel are shown, one for a pipe with a wall thickness of 0.675 cm and one for a pipe with a wall thickness of 0.37 cm. The absorption in both changes gradually on going from the inner boundary of the pipe to the middle. Therefore, the picture on the fluoroscope will not show a perfectly sharp pipe-wall boundary. The boundaries of a liquid film on the wall will be obscured by the effect of variable wall thickness and variable liquid thickness experienced by the X-ray beam. This is of importance for the

Fig. 19a. The Total Wall Thickness (δ) as Function of the Pipe Radius

Fig. 19b. The Absorption of X-rays in Steel and Titanium as Function of the Pipe Radius

interpretation of pictures which show the main liquid flow on the wall. This effect must be taken into consideration if one attempts to evaluate the average film thickness, etc.

The slope of the absorption curve near the inner boundary is larger in the case of the thinner wall, as shown in Fig. 19b. This means that the above-mentioned effect is diminished. The use of titanium produces the same result. All these difficulties are circumvented if a rectangular conduit is used.

A larger pipe diameter will increase the contrast of an annular liquid film because the X-ray beam will traverse more fluid before the beam reaches the image-intensifier tube.

Geometrical Considerations

Figure 20 shows a schematic diagram of the X-ray source, the object, and the image-intensifier tube. The distances p and q have to be optimized to assure that the maximum potential of the system is utilized. If p is small, the amount of photons per cm^2 per sec on the object is large. If p is large, the blurring caused by the finite size of the focal spot,

Fig. 20. Schematic of Arrangement between Focal Spot, Pipe, and Image-intensifier Tube

as explained in a previous section, is small (see Fig. 6). If ℓ is the minimum resolution of the image-intensifier tube, then $1/\ell$ is the smallest dimension of any object that can be seen. If the blurring is smaller than $1/\ell$, the object will not be observed. In order to make the blurring smaller than $1/\ell$, the distance p has to obey the relation

$$p > q(s\ell + 1), \quad (12)$$

in which s is the size of the focal spot. The number of photons per cm^2 per sec on the face of the object is inversely proportional to the square of the distance between the focal spot and the face of the object. Therefore, this number of photons per cm^2 per sec will be large when p is small. However, p is limited by Eq. (12).

If the distance q is not equal to zero, then magnification results. The magnification M is given by

$$M = p/(p - q). \quad (13)$$

The distance q will never be zero because of the space needed for insulation and the collimator, so that magnification will always be present. This is of importance in estimating, for example, the size of bubbles (see Fig. 21).

Fig. 21
Magnification

Data Recording

It is possible to record the pictures obtained by the fluoroscope in one of three ways. (1) A video tape recorder can be connected to the monitor; good reproductions are obtained and immediate playback is possible. (2) A special film camera whose shutter speed is synchronized with the number of frames per sec of the TV system can film directly from the screen. (3) The output of the image-intensifier tube can be filmed with a regular camera if the radiation intensity is not excessive. All three methods will allow determination of quantities such as bubble population, bubble size, bubble velocity, and possibly, average thickness of the liquid film.

The feasibility of employing a specific fluoroscopic system for observing given objects effectively can be determined by solving Eqs. (8), (9), and (10). The solutions to these equations establishes the contrast C , and the minimum perceptible contrast C_{min} . It is possible to obtain an approximate solution of these equations, but a more effective and precise way to establish the workability of the system is to test it. Therefore, studies of two-phase flow patterns were undertaken with air-water and steam-water loops.

III. DESCRIPTION OF EXPERIMENTAL APPARATUS

Air-Water Loop

A schematic diagram of the air-water loop is presented in Fig. 22. The test section has the following characteristics:

Structural material	aluminum
Geometry	round
Inner diameter	2.665 cm (1.049 in.)
Wall thickness	0.338 cm (0.133 in.)
Length-to-diameter ratio	60
Orientation	vertical

The fluoroscope has the following characteristics:

The X-ray tube: maximum voltage 110 kV; half-wave rectified;
maximum current at 110 kV, 4 mA;
size of focal spot 2 mm.

The image-intensifier tube: brightness gain - 3000
minimum resolution - 70 lines/in.

The TV system: camera type - vidicon
horizontal resolution - 600 lines
bandwidth - 8 Mcps.

Fig. 22. Schematic Diagram
of Air-Water Loop

The X-ray tube during this experiment was operated at 70 kV and 4 mA. The distance between focal spot and the inner screen of the image-intensifier tube was 28 cm (11.024 in.). The distance between pipe and input screen was 4.5 cm (1.772 in.).

Comparing the above fluoroscopic system with the "ideal" fluoroscope as described in the preceding section, the following deviations are apparent: (1) the X-ray tube has a large focal spot; the maximum voltage is low and half-wave rectified; (2) the TV system uses a vidicon camera and the resolution is only 600 lines.

It should be noted that because the test section was an aluminum pipe, the limitation on the voltage is not too important.

Various flow patterns within the test section were generated by varying the water and air flow rates. After passing the test section, the mixture flowed through a Plexiglass pipe of the same inner diameter as the test section. This enabled the operator to compare the picture of the flow pattern obtained on the fluoroscope with the direct view of the same pattern through the Plexiglass.

Steam-Water Loop

A schematic diagram of the steam-water loop is given in Fig. 23. Studies of flow patterns and transition points were made in two different test sections described briefly below.

Test Section I

Structural material	stainless steel 304
Geometry	round
Inner diameter	2.665 cm (1.049 in.)
Wall thickness	0.170 cm (0.07 in.)
Length to diameter ratio	50
Orientation	vertical

Fig. 23. Schematic Diagram of Steam-Water Loop

The stated wall thickness is the one at the position of the fluoroscope. The remainder of the pipe had a wall thickness of 0.338 cm (0.133 in.).

Test Section II

Structural material	stainless steel 304
Geometry	round
Inner diameter	5.479 cm (2.157 in.)
Wall thickness	0.277 cm (0.109 in.)
Length to diameter ratio	25
Orientation	vertical

Several components of the fluoroscope used on the steam-water loop were different from the ones used on the air-water loop. They were:

The X-ray tube - maximum voltage, 150 kV, fully rectified;
maximum current at 150 kV, 6 mA;
size focal spot 0.3 mm.

The TV System - camera type, vidicon
horizontal resolution, 800 lines
bandwidth, 12 Mcps.

The X-ray tube compares with the one from the "ideal" fluoroscope. The TV system has a good resolution but the camera again was a vidicon. The operating conditions for the X-ray tube were (1) 110 kV and 6 mA for the first test section, and (2) 130 kV and 6 mA for the second test section. The distance between focal spot and pipe was 40 cm (15.748 in.). The distance between pipe and input screen of the image-intensifier tube was 15 cm (5.905 in.). Figure 23a shows a photograph of the fluoroscope installed on the steam-water loop. Figure 23b is a closeup of the same arrangement shown in Fig. 23a.

The steam-water loop was operated at pressures ranging from 200 to 800 psia for the first test section, and from 200 to 600 psia for the second test section. An air-operated valve between the steam separator and the condenser controlled the amount of steam flowing to the condenser and therefore controlled the pressure.

Fig. 23a The Fluoroscope Installed on the Steam-Water Loop

Fig. 23b

Closeup of the Fluoroscope

All data were taken by keeping the water flow rate constant and varying the steam flow rate. The flow rates investigated ranged between the following values:

Test Section I

Water flow rate	0.1 to 0.4 lb/sec
Steam flow rate	0.005 to 0.09 lb/sec

Test Section II

Water flow rate	0.15 to 0.6 lb/sec
Steam flow rate	0.005 to 0.1 lb/sec

The flow was always allowed to stabilize out before any data were taken. The flow rates were measured with knife-edged orifices. To accommodate the wide variety of steam flows, two orifices of different size were used to measure the steam flow. The pressure drop was also measured across the test section.

IV. EXPERIMENTAL RESULTS

During both the air-water and steam-water tests, the flow patterns schematically illustrated in Fig. 24 were observed.

Bubble Flow (Fig. 24a). The steam flows in bubbles of different sizes through the liquid. The size and the number of bubbles increase as the quality is increased. In the 2.157-in. test section, the bubble flow had the following characteristics: bubbles of all sizes were moving in large spirals; the larger bubbles were strongly deformed and never had a diameter larger than about $2/3$ of the pipe diameter. Many small bubbles moved in strong vortices in the wake of the larger bubbles (see Fig. 25).

Fig. 24. Two-phase Flow Patterns

Fig. 25

Sketch of Bubble
Flow in a
2.157-in. Pipe

Slug Flow (Fig. 24b). The steam flows in bubble-shaped slugs, filling almost the whole diameter of the pipe (Taylor bubbles). The length of the gas slug increases as the quality increases. Also, small bubbles may occur in the wake of the slug.

Churn Flow (Fig. 24c). The flow has a very turbulent character. The Taylor bubbles have completely disappeared. The liquid is strongly accelerated and de-accelerated. In particular, at the lower qualities it has been observed that the liquid temporarily falls back and fills the whole tube diameter for a short time before it shoots up again. With increase of quality, the liquid flows more and more on the walls with large waves. The accelerations and de-accelerations still persist. The higher the quality, the more directional is the movement of the liquid.

Annular Flow (Fig. 24d). The vigorous turbulent motions as observed in churn flow disappear. The liquid flows as a wavy film on the wall. No accelerations and de-accelerations are observed anymore.

Although the various flow patterns could be viewed readily on the TV monitor, acceptable single-frame still photographs could not be obtained, primarily because a single frame taken from a movie does not contain sufficient information or detail. However, such frames when following one another in rapid succession during playback on a TV monitor or screen produce a very acceptable image. The quality of the single-frame exposure is very poor in comparison.

The movement of the two-phase mixtures strongly affects the picture quality one can obtain on the TV monitor. A certain amount of movement is very beneficial and facilitates observation in low-contrast systems. However, when the velocity becomes excessive, blurring occurs and the picture quality degenerates. This is due to the persistence of the image on the output screen of the image-intensifier tube. The brightness of the output phosphor screen decreases to 5% of the original brightness in 0.2 sec. Fast-moving voids or droplets can travel a substantial distance in this time and therefore would be viewed as a blur instead of as a distinct object.

The fluoroscope worked very well with the air-water loop. Tests with this system were essentially preliminary in nature. All the above-mentioned flow patterns could be observed, including the transition points. Sheets of stainless steel were inserted between X-ray tube and pipe to investigate the possibility of scanning the two-phase flow through a stainless steel pipe. The flow patterns could still be observed if the total thickness of stainless steel sheets inserted was less than 0.180 in.; for this condition the X-ray tube was operated at 100 kV and 4 mA. The contrast, however, was noticeably smaller. It should be noted that the layer of stainless steel was flat; curved layers as exist in round tubes will distort the picture, as explained previously.

Similar successful results were obtained with the steam-water loop operated under elevated pressures. Originally, an attempt was made to penetrate a test section with a wall thickness of 0.133 in. Operation of the X-ray tube at 150 kV and 6 mA resulted in low picture quality in the regions of churn flow and annular flow. This could be attributed to the influence of the pipe roundness. Therefore the pipe wall thickness was reduced to 0.07 in. at the position on the fluoroscope. Good pictures were then obtained for all flow patterns.

Excellent pictures were obtained with the second test section, for which the influence of the pipe roundness was much less than that of the smaller-diameter pipe test section.

Preliminary results on flow patterns in steam-water mixtures at pressures up to 800 psi were obtained as a byproduct of this study and are presented in Tables 1 to 6. These tables show the flow rate of the steam and of the liquid; the pressure drop per unit length of pipe; and the observed flow pattern. Tables 1 to 3 give the results for Test Section I for pressures 305, 575, and 765 psia, respectively. Tables 4 to 6 give the results for Test Section II for pressures of 190, 385, and 575 psia, respectively.

Table 1

FLOW RATE AND PRESSURE DROP DATA FOR 385 psia AND 1.049-in.-DIAMETER CHANNEL

Run No.	Pressure Drop per Unit Length, psi/ft	$W_g \times 10^{-2}$, lb/sec	$W_f \times 10^{-1}$, lb/sec	Q_g , ft ³ /sec	Q_f , ft ³ /sec	$\frac{Q_g}{Q_g + Q_f}$	NFr	Flow Pattern
B1	18.53	0.485	0.7	0.0058	0.00135	0.814	0.518	slug
B1 ^a	-	1.42	1.02	0.0171	0.00197	0.868	3.64	slug
B3	34.29	1.48	1.07	0.0178	0.00206	0.896	3.96	churn
B4	40.84	2.51	1.12	0.0303	0.00214	0.935	10.58	churn
C1	46.84	3.81	1.07	0.0458	0.00206	0.957	23	churn
C2	49.18	5.98	1.12	0.0722	0.00214	0.97	55.5	annular
B5	24.35	0.825	2.15	0.0099	0.00414	0.706	2.01	slug
B6	31.62	1.29	1.77	0.0155	0.0034	0.82	3.57	churn
C3	40.62	2.51	1.91	0.0302	0.00367	0.88	11.55	churn
B7	41.03	2.96	1.81	0.0357	0.00349	0.91	15.4	churn
C4	44.12	3.27	1.91	0.0394	0.00367	0.915	18.65	churn
C5	44.90	4.15	1.91	0.05	0.0036	0.93	28.9	transition churn
C6	46.84	5.10	1.95	0.0614	0.00375	0.94	42.6	annular
B8	16.97	0.682	3.22	0.00821	0.00619	0.57	2.08	slug
B9	22.79	0.917	3.29	0.01105	0.00633	0.633	3.03	churn
B10	25.41	1.035	3.38	0.0125	0.0065	0.657	3.63	churn
C9	37.51	2.335	3.41	0.0281	0.00656	0.81	12.05	churn
C8	41.79	3.46	3.32	0.0417	0.00638	0.866	23.2	transition churn

Table 2

FLOW RATE AND PRESSURE DROP DATA FOR 575 psia AND 1.049-in.-DIAMETER CHANNEL

Run No.	Pressure Drop per Unit Length, psi/ft	$W_g \times 10^{-2}$, lb/sec	$W_f \times 10^{-1}$, lb/sec	Q_g , ft ³ /sec	Q_f , ft ³ /sec	$\frac{Q_g}{Q_g + Q_f}$	NFr	Flow Pattern
D1	19.05	0.737	0.548	0.0058	0.001	0.855	0.47	slug
D2	24.30	0.896	0.548	0.0072	0.001	0.88	0.68	transition slug
D3	31.68	1.303	0.548	0.0105	0.001	0.91	1.33	churn
D4	33.43	1.53	0.548	0.0123	0.001	0.925	1.78	churn
D5	47.82	4.45	0.548	0.0358	0.001	0.97	13.6	churn
D6	19.05	0.832	1.457	0.0067	0.0029	0.70	0.925	slug
D7	23.71	1.075	1.457	0.0087	0.0029	0.75	1.35	transition slug
D8	28.77	1.34	1.457	0.0108	0.0029	0.79	1.89	churn
C10	41.98	4.16	2.18	0.0335	0.0044	0.885	14.45	churn
C11	45.87	5.66	2.23	0.0457	0.0045	0.91	25.3	annular
C12	46.26	6.55	2.23	0.0528	0.0045	0.92	33	annular
D10	16.52	0.845	2.64	0.0068	0.0053	0.56	1.47	slug
D9	23.32	1.37	2.64	0.0113	0.0053	0.68	2.77	churn
C13	40.43	4.22	3.43	0.034	0.0069	0.83	16.8	churn
C14	44.12	6.76	3.52	0.0545	0.0071	0.885	38.1	annular
C15	44.90	8.73	3.475	0.0704	0.0070	0.91	60.2	annular

Table 3

FLOW RATE AND PRESSURE DROP DATA FOR 765 psia AND 1.049-in.-DIAMETER CHANNEL

Run No.	Pressure Drop per Unit Length, psi/ft	$W_g \times 10^{-2}$, lb/sec	$W_f \times 10^{-1}$, lb/sec	Q_g , ft ³ /sec	Q_f , ft ³ /sec	$\frac{Q_g}{Q_g + Q_f}$	NFr	Flow Pattern
D12	21.58	0.90	0.627	0.0054	0.0013	0.805	0.445	slug
D11	24.69	1.12	0.627	0.0066	0.0013	0.835	0.63	transition slug
D13	29.74	1.565	0.627	0.0093	0.0013	0.88	1.13	churn
E2	45.68	5.25	0.985	0.0311	0.002	0.94	11	transition churn
E3	48.20	6.6	0.985	0.0392	0.002	0.95	17	annular
D15	13.61	0.92	1.88	0.00545	0.0039	0.65	0.70	slug
D14	24.49	1.56	1.97	0.00925	0.0041	0.70	1.78	churn
E6	18.08	3.14	4.13	0.0186	0.0086	0.685	7.43	churn
E5	38.29	4.72	3.77	0.028	0.0078	0.78	12.88	transition churn
E4	41.79	6.78	3.82	0.0402	0.00795	0.835	23.2	annular

Table 4

FLOW RATE AND PRESSURE DROP DATA FOR 190 psia AND 2.157-in.-DIAMETER CHANNEL

Run No.	Pressure Drop per Unit Length, psi/ft	$W_g \times 10^{-2}$, lb/sec	$W_f \times 10^{-1}$, lb/sec	Q_g , ft ³ /sec	Q_f , ft ³ /sec	$\frac{Q_g}{Q_g + Q_f}$	NFr	Flow Pattern
G21	11.62	0.49	1.53	0.0114	0.0028	0.80	0.055	bubble
G22	14.15	0.56	1.53	0.0129	0.0028	0.82	0.067	bubble
G23	21.98	0.68	1.6	0.0158	0.0029	0.845	0.095	bubble
G24	21.98	0.83	1.6	0.0192	0.0029	0.87	0.132	churn
G24 ^a	21.98	0.81	5.5	0.0188	0.0084	0.69	0.20	bubble
G25	21.98	0.85	5.5	0.0197	0.0084	0.70	0.215	churn
F6	52.81	2.88	0.55	0.067	0.00096	0.985	1.25	churn

Table 5

FLOW RATE AND PRESSURE DROP DATA FOR 385 psia AND 2.157-in.-DIAMETER CHANNEL

Run No.	Pressure Drop per Unit Length, psi/ft	$W_g \times 10^{-2}$, lb/sec	$W_f \times 10^{-1}$, lb/sec	Q_g , ft ³ /sec	Q_f , ft ³ /sec	$\frac{Q_g}{Q_g + Q_f}$	NFr	Flow Pattern
G1	13.14	0.71	1.63	0.0086	0.0031	0.73	0.037	bubble
G2	15.67	0.85	1.63	0.0102	0.0031	0.77	0.048	bubble
G3	19.96	1.315	1.63	0.0158	0.0031	0.835	0.097	transition bubble
G4	21.23	1.535	1.63	0.0185	0.0031	0.855	0.127	churn
G5	21.73	1.68	1.63	0.0202	0.0031	0.865	0.147	churn
F2	39.17	5.47	2.37	0.0658	0.0046	0.935	1.34	churn
F4	47.25	9.81	1.86	0.118	0.00375	0.97	4.40	churn
G9	17.18	0.55	0.28	0.00665	0.00054	0.925	0.014	bubble
G8	18.95	0.77	0.33	0.0093	0.00063	0.935	0.027	transition bubble
G7	23.50	1.24	0.33	0.0149	0.00063	0.96	0.065	churn
G10	14.15	0.81	4.02	0.00975	0.0077	0.56	0.083	bubble
G11	16.93	0.98	4.06	0.01175	0.0078	0.60	0.103	transition bubble
G12	18.19	1.12	4.10	0.0135	0.0079	0.63	0.124	churn
G13	19.71	1.375	4.10	0.0166	0.0079	0.68	0.163	churn
G14	22.24	1.77	4.10	0.0214	0.0079	0.73	0.233	churn
G17	13.39	0.695	5.97	0.0084	0.01145	0.42	0.106	bubble
G16	17.18	1.13	6.03	0.01365	0.0116	0.54	0.173	transition bubble
G15	21.73	1.69	6.06	0.0203	0.0117	0.64	0.277	churn

Table 6

FLOW RATE AND PRESSURE DROP DATA FOR 575 psia AND 2.157-in.-DIAMETER CHANNEL

Run No.	Pressure Drop per Unit Length, psi/ft	$W_g \times 10^{-2}$, lb/sec	$W_f \times 10^{-1}$, lb/sec	Q_g , ft ³ /sec	Q_f , ft ³ /sec	$\frac{Q_g}{Q_g + Q_f}$	NFr	Flow Pattern
G19	13.39	0.72	1.775	0.0058	0.0036	0.62	0.024	bubble
G18	17.43	1.11	1.875	0.0090	0.00375	0.71	0.044	bubble
G20	19.96	1.47	1.875	0.0119	0.00375	0.76	0.0665	churn

These data are plotted on the graphs shown in Figs. 26-29. The variables were grouped in two dimensionless numbers, namely, (1) the volumetric quality, defined as the ratio of the volumetric gas rate and the total volumetric flow rates of gas and liquid, and (2) the Froude number, given by

$$N_{Fr} = \frac{(Q_g + Q_f)^2}{A^2 D g},$$

in which

Q_g = the volumetric flow rate of the gas, ft³/sec

Q_f = the volumetric flow rate of the fluid, ft³/sec

A = the cross-sectional area of the pipe, ft²

g = the acceleration of gravity, ft/sec²

D = the inner diameter of the flow channel.

Fig. 26

Flow Map for 385 psia and 1.049-in. Pipe

$$\text{The Volumetric Quality} = \frac{Q_g}{Q_g + Q_f}$$

$$\text{The Froude Number} = \frac{(Q_g + Q_f)^2}{A^2 D g}$$

Fig. 27

Flow Map for 575 psia and 1.049-in. Pipe

$$\text{The Volumetric Quality} = \frac{Q_g}{Q_g + Q_f}$$

$$\text{The Froude Number} = \frac{(Q_g + Q_f)^2}{A^2 D g}$$

Fig. 28

Flow Map for 765 psia and 1.049-in. Pipe

$$\text{The Volumetric Quality} = \frac{Q_g}{Q_g + Q_f}$$

$$\text{The Froude Number} = \frac{(Q_g + Q_f)^2}{A^2 D g}$$

Fig. 29. Flow Maps for 190, 385, and 575 psia and 2.157-in. Pipe

$$\text{The Volumetric Quality} = \frac{Q_g}{Q_g + Q_f}$$

$$\text{The Froude Number} = \frac{(Q_g + Q_f)^2}{A^2 D g}$$

changed directly to churn flow if the quality of the mixture was increased.

2. At the higher pressures and in the 1.049-in. test section it was noticed that under certain conditions slug flow suddenly collapsed into churn flow, after which the slug flow pattern reemerged. These points are labeled as transition slug flow and are thought to be caused by small pressure oscillations. A similar behavior was noticed in the 2.157-in. test section, but occurred between bubble and churn flow.

3. In the 1.049-in. test section, the slug-churn transition took place at a lower Froude number when the pressure was increased. In the 2.157-in. test section the bubble-to-churn flow transition took place also at lower Froude numbers if the pressure was increased. In both cases a higher Froude number was found by lower volume qualities.

4. A transition churn flow could be observed in which annular flow from time to time collapsed into churn flow.

5. The points for annular flow compare reasonably well with the proposed boundary lines.

The dashed lines in Figs. 26 to 29 indicate the boundaries of the different flow patterns as proposed by Griffith and Wallis.⁽¹⁰⁾ The actual data are denoted by the various symbols. It should be noted that the boundary lines should actually be considered as bands. Figures 26 to 28 contain data taken from the first test section; Fig. 29 contains data taken from the second test section.

The following trends were noted from these preliminary flow pattern studies:

1. In the 1.049-in. test section, slug flow could be obtained at all pressures investigated. In the 2.157-in. test section, however, no slug flow could be obtained over the pressure range studied. Bubble flow

changed directly to churn flow if the quality of the mixture was increased.

V. CONCLUSIONS

The fluoroscope worked as expected. It can be used successfully for the study of two-phase flow patterns in high-pressure systems. Generally, it is a powerful tool for the study of phenomena which can occur in the simultaneous flow of mixtures composed of different phases of different components, or both. With the proper components, the fluoroscope can detect radiation that penetrates stainless steel pipes with a wall thickness ranging from 0.07 to 0.109 in. Bubble flow, slug flow, churn flow, and annular flow, including their transition points, can be perceived with good quality. In particular, slug flow and its transitions can be observed very well.

The velocity of the mixture, however, is limited. For a pipe with an inner diameter of 1.049 in. it was found that one can discern between bubble, slug, churn, and annular flows if the liquid flow rate is below a superficial liquid velocity of 1.05 ft/sec.

It was also determined that round pipes diminish the picture quality considerably, as was expected from the theoretical considerations.

The pictures obtained on the monitor can be successfully recorded on film or on videotape. Still pictures of these recordings, however, lack detailed information.

VI. RECOMMENDATIONS

The components of the fluoroscope can be improved by:

1. An X-ray tube which can obtain higher intensities. Large maximum currents are advantageous because a higher intensity is obtained without higher voltage.
2. An image-intensifier tube with a higher brightness gain. The use of a special phosphor screen which can increase the contrast can enlarge the usefulness of the fluoroscope.
3. An orthicon TV system with a resolution of the order of 1000 TV lines.
4. The use of titanium conduits for high-pressure studies is also strongly recommended.

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