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TWO-PHASE FLOW MODEL TEST FACILITY

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This report includes the report for Phase I, Task 1 of the SAFETY VALVE STUDY project at the University of Maryland.

16. Abstract

This report describes test facilities for the investigation of two-phase flows. These facilities were developed under Phase I and built under Phase II of a DOT sponsored program entitled "SAFETY VALVE STUDY" which is being carried out at the University of Maryland, Department of Mechanical Engineering. The test facility completed to this date consists of the Blow-Down Test Apparatus and the Bubble and Slug Flow Tunnel. It is the purpose of the test facilities to support, test and aid in the development of safety valve sizing equations when different two-phase regimes occur.

17. Key Words
Two-Phase Flow, Flashing Flow, Bubble and Slug Flow, Flow of Freon-12 , Mass Flow Rates of Propane.

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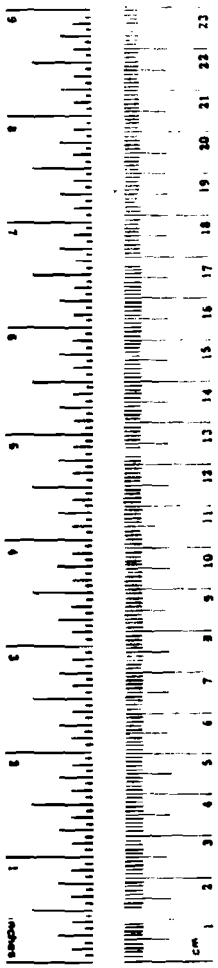
METRIC CONVERSION FACTORS

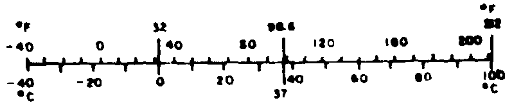
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



I. Introduction

A recent report* by the Committee on Hazardous Materials of the National Academy of Sciences raises serious questions as to the adequacy of pressure relief capacities of safety valves currently in use on railroad tank cars and marine vessels. The central question is: "Will a safety valve, which is designed to relieve pressure by exhausting vapor at a specified volume flow rate to the atmosphere, also have the same specified volume flow rate if the fluid flowing through the valve is in its liquid phase or is a two-phase mixture of liquid and vapor?" The brief NAS study* negates this question by comparing the flow velocities of the liquid phase with that of the vapor phase, namely

$$V_f = [2g_c\,(P_0 - P)v_f]^{1/2} \quad \text{(for liquid)} \qquad (1)$$

and

$$V_g \simeq \left[\frac{2g_c(P_0 - P)v_g}{1 - \frac{1}{4}(V_g/C_0)^2}\right]^{1/2} \quad \text{(for vapor)} \qquad (2)$$

where g_c = 32.2 (lbm)(ft)/(lbf)(sec^2)

P_0 = Inlet pressure, psfa

P = Exit pressure, psfa

C_0 = Sonic speed at inlet conditions, ft/sec

V_f, V_g = Velocity of the liquid and vapor, respectively

v_f, v_g = Specific volume of the liquid and the vapor, respectively.

Evaluations using saturated propane at 138°F given by the NAS study determine liquid volume flow rates to be about 3 times less than required (when equations (1) and (2) are used), and almost 5 times less than required when liquid propane flushes into vapor during the flow process.

A closer examination of equation (2) shows that it is only valid if $V_g << C_0$, i.e. at Mach number M much less than one. (It is customary to make this assumption in low speed fluid dynamics when $M < 0.3$; the error then introduced is less than 2% while for higher Mach numbers the error increases exponentially.) Flow of a gas or of a high quality vapor from a reservoir at pressure P_0 to the atmosphere through a nozzle or valve will choke the nozzle

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* "Pressure-Relieving Systems for Marine Cargo Bulk Liquid Containers," Committee on Hazardous Materials, National Academy of Sciences, Washington, D.C., 1973.

if the pressure ratio P_0/P_{atm} equals or exceeds the critical value

$$\left(\frac{P_0}{P_{atm}}\right)_{crit} = \left(1 + \frac{k-1}{2}\right)^{\frac{k}{k-1}} \qquad (3)$$

where $k = \frac{C_p}{C_v}$ and C_p and C_v are the specific heats at a constant pressure and constant volume, respectively. For dry propane vapor $k = 1.33$ so that the critical pressure ratio becomes 1.8506, i.e., choked flow will exist as long as the pressure of the propane vapor is larger than 27.2 psia. Excluding arctic low ambient temperatures, the vapor pressure of propane in railroad tank cars will always exceed this critical pressure as long as some liquid propane is present. Therefore, the velocity at the minimum cross sectional area will simply be the sonic velocity at the throat of the nozzle or the valve, namely

$$c^* = c_0 \sqrt{\frac{2}{k+1}} \qquad (4)$$

and the maximum mass flow rate becomes

$$\left(\frac{\dot{m}}{A}\right)_{max} = \frac{P_0}{\sqrt{T_0}} \sqrt{\frac{kg_c}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \qquad (5)$$

where A is the minimum area in sq. ft. and R is the gas constant; for propane $R = 35.036 \frac{\text{ft-lbf}}{\text{lbm-}^\circ\text{R}}$.

While the equations (4) and (5) are sufficiently accurate for the prediction of velocity and mass flow rate of a highly superheated vapor, to this date little or no knowledge exists which permits a sufficiently accurate prediction of flow rates when the liquid and the vapor phase occur simultaneously. In particular, the following phenomena or flow regimes are likely to occur in the valve:

1. High Quality Vapor Flow. Flow rate equations for this flow can be developed by modifying the conventional perfect gas--isentropic flow approach. The full sized test facility at Edwards Air Force Base adequately tests valves under these conditions.

2. Spray, Mist, Bubble and Slug Flow. This is flow of a mixture where liquid and vapor exists simultaneously. The mixture may be in the form of liquid droplets and vapor or in form of vapor bubbles in liquid or in alternate liquid-vapor slugs. If there is no slip between the phases, the flow is called mist

flow. Mist flow is not restricted to a high quality regime. Presently little is known about this type of flow. However, since sonic velocity of such a spray mixture has been observed to be very low, this flow must be investigated. For instance, the sonic velocity of a water spray -- air mixture may be as low as 1/10 the sonic velocity of air alone. It is plausible that for choked spray flow the critical flow rate will also be strongly dependent upon the sonic velocity of the mixture as it is the case for the flow of a perfect gas, see equation (4). This has to be investigated and proper prediction equations for sizing the valve must be developed. To support the stipulation of the physical models underlying the theory and to test the developed equations, experimental evidence and results are necessary. The existing full sized facility does not permit such tests. Because of the physical size, it is not feasible to modify the existing full scale facility since optical observations (laser-doppler technique) are required to monitor velocity.

3. Annular Flow. This flow is the flow of a liquid-vapor mixture where the liquid forms a jet-like core and the vapor forms a jacket around the liquid phase. In this case, as was the case in the above case, the relative velocity between the liquid phase and the gas phase must be measured and the dependence of this slip velocity upon such parameters as upstream pressure and temperature must be found. Optical techniques are again necessary. The full scale test facility does not permit installation of such devices and its size makes an experimental parametric study not feasible. Before any elaborate test stand is built it should be shown that, one, annular flow can indeed be established in the safety vale, and two, that annular flow will then determine the maximum mass flow, i.e. that annular flow is the the choking mechanism.

4. Total Flashing Flow. In this flow regime only liquid enters the valve and total flashing (a complete change of phase from liquid to vapor) occurs within the valve. This circumstance is brought about when the railroad tank car falls on its side as it has been observed to do in derailment accidents. An experimental parametric study must be made which not only shows the dependence of the discharge rates upon the upstream pressures and temperatures but also clarifies the influence of the valve shape on the flashing characteristics.

This report describes the experimental two-phase flow facilities which were developed under Phase I and built under Phase II of the DOT sponsored SAFETY VALVE STUDY at the University of Maryland, Department of Mechanical Engineering, (Contract Number DOT-FR-64181).

II. Preliminary Discussion of Existing Mass Flow Prediction Equations when Slip Flow is Present

The technical literature on two-phase critical flow is very extensive. Existing analyses and models for critical mass flow rates which are most applicable to the propane safety valve problem are those by H. K. Fauske (ANL-6633, 1962), F. J. Moody (J. Heat Transfer, 1965), S. Levy (J. Heat Transfer, 1965), J. E. Cruver and R. W. Moulton (J. AICHE, 1967), R. E. Henry (Mech. Soc. Eng., 1970), and by R. E. Henry and H. K. Fauske (J. Heat Transfer, 1971).

The complexity of predicting critical mass flow rates of two-phase flows was in part described in the Monthly Letter Report No. 4 (dated October 9, 1975) and the Monthly Letter Report No. 5 (dated November 12, 1975). The revised and extended results which result from these different flow models will be described in report FRA-ORD 76/301. In summary, the cited Letter Reports do not only give an indication of the complexity of the problem but also show a totally unacceptable difference in predicted mass flow rates. It was found that for low quality propane mixtures the predictions using models published in the technical literature may differ by a factor of 60 or more! In addition, the models in their present form are only valid for flow through straight circular tubes and not applicable to flows through nozzles which have a complex boundary geometry.

During the investigations under Phase I of this contract, a new simplified flow model was developed. The underlying physical principles of this model are as follows: the two-phase mixture is considered to be a homogeneous mixture of saturated vapor and saturated liquid droplets. If the quality is very high, say near 1.0, then there are very few droplets of liquid per unit volume, while when the quality is very low there are very many droplets per unit volume. In critical flow, the vapor is assumed to have sonic velocity while the liquid droplets move at somewhat lower velocity. The slip velocity ratio is not known a priori, and has to be measured or deduced by analytical means. This new simplified model, hence called the Sallet-Wu-model, is likely to be applicable to flows having complex flow patterns such as the flow through plug-nozzles with orifices. This is derived from the fact that the slip velocity will be dependent upon the curvature of the stream lines and upon the convective acceleration of the fluid within the nozzle. It is for this reason that careful and systematic measurements of the slip velocity and simultaneous flow visualization must be undertaken

III. Two-Phase Flow Model Test Facility

The Two-Phase Flow Model Test Facility to be assembled at the University of Maryland (Department of Mechanical Engineering) consists of 4 test systems. These test systems are:

a. The Blow-Down Test Apparatus
(to be designed under Phase I and to built under Phase II of the Safety Valve Study)

b. The Bubble and Slug Flow Tunnel
(to be designed under Phase I and to be built under Phase II of the Safety Valve Study)

c. The Full Scale Spray Flow Test Apparatus
(to be designed and built under Phase III of the Safety Valve Study)

d. The Flow Pattern Visualization Equipment
(not required by contract but a necessary extension)

The first two test systems (a and b) were designed and built and are described in this report. The latter two systems (c and d) are under development and are not described in this report.

IV-1 The Blow-Down Test Apparatus

When a fluid of low boiling point such as propane which has a high saturation pressure at ambient temperatures is exposed to a low pressure, heavy pool boiling and flashing will occur. An example of heavy pool boiling is shown in Figure 4.1. It is the purpose of the Blow-Down Test Apparatus to measure mass flow rates of such a flashing fluid and to measure and observe its behavior during blow-down.

Figure 4.2 shows an overall view of the Blow-Down Test Apparatus and Figure 4.3 shows a close-up of the Blow-Down Vessel. The apparatus permits measurements in which the exit orifice initially "sees" vapor; as shown in Figures 4.2 and 4.3 and measurements in which the exit orifice initially "sees" liquid. In the latter case, the vessel sits on top (upside down) of the Strain Gage Balance Beam (see Figure 4.4). The Blow-Down Vessel has an inside diameter of 80 mm and is 240mm high. Different orifices or nozzles can be mounted into the end plate of the vessel. The opening valve is downstream from the orifice or nozzle which represents the critical section of the scaled safety valve. The mass flow rate, the mass which has left the vessel, the temperatures at 10 different locations and the pressure at two locations are measured and recorded during blow-down. It should be noted that the pressure transducer at the bottom of the vessel (see Figure 4.3) is thermally separated from the Freon in the vessel by a flexible membrane on the bottom plate.

Typical boiling of the fluid inside the vessel can be observed when the vessel is made out of plexiglas. Figure 4.5 shows steady boiling of Freon-12 during blow-down when the exit orifice is small (1.6 mm diameter). Figure 4.6 and 4.7 show the heavy pool boiling when the orifice is larger (4.8 mm diameter). Figure 4.6 is a photograph which was made immediately after the start of blow-down test, while the photograph given by Figure 4.7 was taken several seconds later. It is seen that the boiling inside the vessel may very well influence the type of flow which exists through the safety valve and with it the mass flow rate.

Figures 4.8, 4.9 and 4.10 show typical outflow behavior during blow-down. In the test during which the photographs for Figure 4.8 and 4.9 were taken the orifice initially (i.e. before the start of the test) sees vapor only, while for Figure 4.10 the orifice sees initially liquid only.

IV-2 The Bubble and Slug Flow Tunnel

The purpose of the Bubble and Slug Flow Tunnel is to make detailed investigations of two-phase flow phenomena through different nozzle and valve sections. The two-phase, one component flow is simulated in a circulating water tunnel which permits air injection.

Figure 4.11 shows an overall view of the Bubble and Slug Flow Tunnel and Figure 4.12 gives a schematic of the tunnel.

The above stated investigation requires the measurement of mass flow rate, slip ratio stagnation pressure loss; static pressure variation and flow pattern for bubble and slug flow through diverse nozzle and valve sections. The flow tunnel which was built allows the following variations:

1. Velocity of liquid phase (0 to 8 m/s)
2. Bubble concentration (from single bubble to slug flow)
3. Bubble diameter
4. Geometry of test section
5. Geometry of valve and nozzle sections
6. Flow direction in relation to gravity

The instrumentation of the flow tunnel permits the measurement of the following parameters:

1. Velocity of water in presence of bubbles
2. Mass flow rate of water
3. Volume flow rate of air
4. Static and total pressures at several locations
5. Size of bubbles
6. Path and velocity of bubbles

Close-up view of the test and bubble introduction sections with different bubble size and concentration are shown in Figure 4.13a and 4.13b.

The exact measurement of flow velocities in two-phase flow leads to many experimental difficulties with the usual measurement techniques. The recently developed laser-doppler anemometry circumvents these undue difficulties and is used here for that reason. The laser-doppler anemometer with accessories is seen in Figure 4.14 and 4.15.

The principal of the laser-doppler anemometer is as follows:

A laser light beam is scattered in all directions from particles in a fluid flow. By combining two incident laser beams a cross-section is formed which consists of a fringe pattern, i.e. of alternate light and dark fringes. Thus a particle passing through the fringe system will emit light pulses at a frequency f_D which is dependent upon the particle velocity, the wavelength of the incident laser light and the crossing angle of the two laser beams. The Doppler frequency f_D is proportional to the particle velocity. Precondition for getting a Doppler signal is the existence of scattering particles in the fluid. The diameter should be about 1 μm or less. If the concentration of scattering particles is too low the flow has to be seeded. The LDA equipment consists of a laser with at least 5 mw output; an optical unit which causes the beam separation and beam intersection; the receiving optics with a photomultiplier; and a laser Doppler signal processor, in our case an LDA Counter Processor which evaluates the instantaneous velocity of a fluid flow. A schematic of the laser optics is shown in Figure 4.16 and a typical fringe pattern is shown in Figure 4.17.

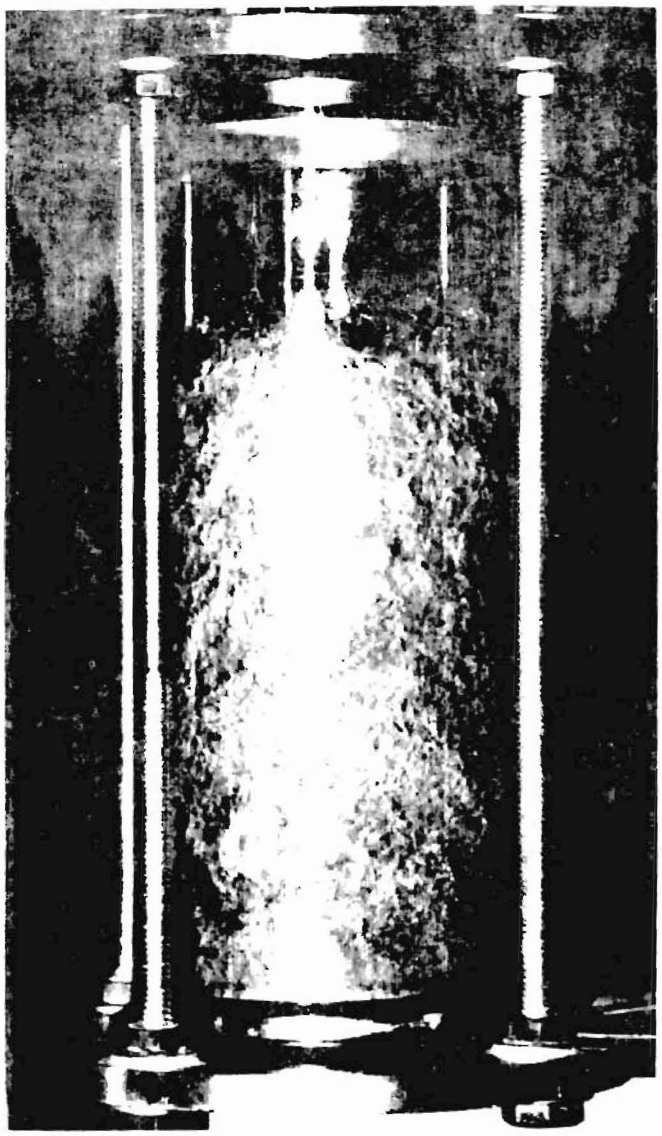

Figure 4.1 Example of Pool Boiling in Pressure Vessel Due to Pressure Relief (medium is Freon 12)

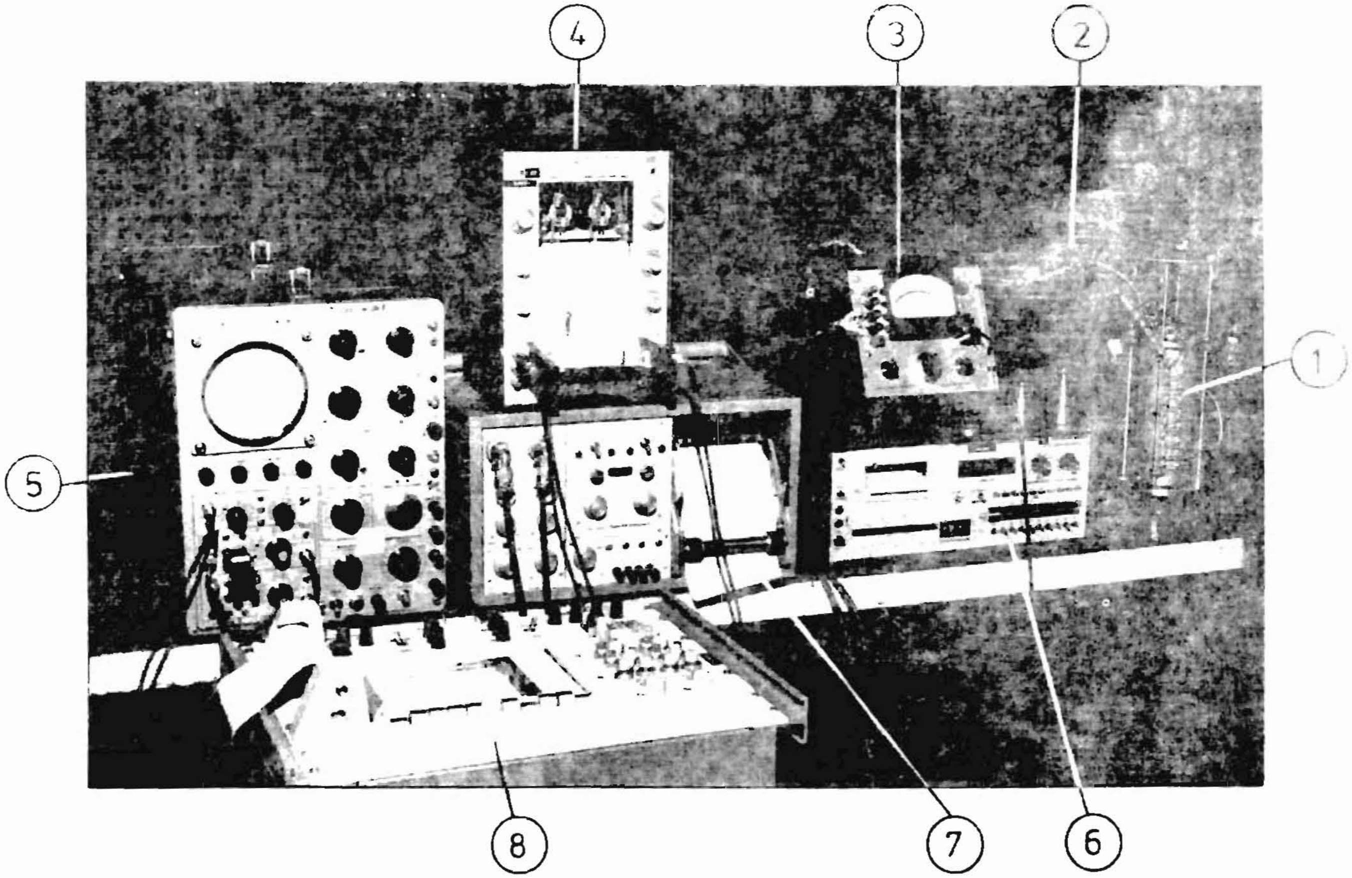

Figure 4.2 Overview of Blow-Down Test Apparatus

1. Blow-Down Vessel
2. Strain Gage Balance Beam
3. Strain Gage Bridge Amplifier
4. Two-Channel Plotter (for mass and mass flow rate)
5. Oscilloscope with Differentiator Plug-In
6. Multichannel Digital Printer (for temp. recording)
7. Two-Channel Plotter (for continuous temp monitoring)
8. Two-Channel Plotter (for continuous press. monitoring)

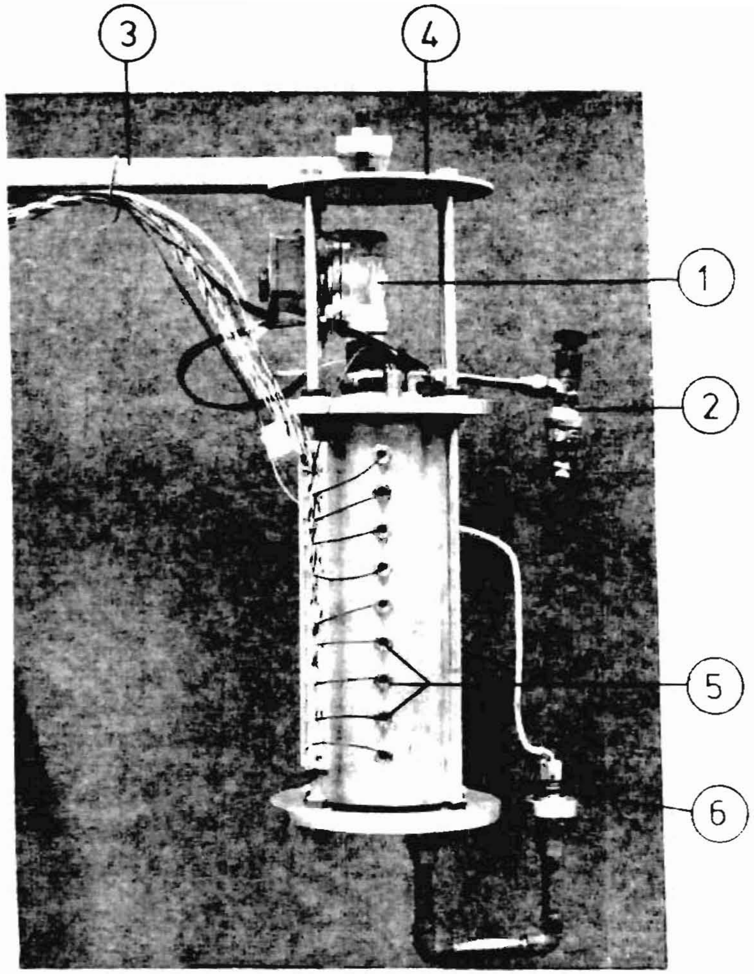

Figure 4.3 Blow-Down Vessel

1. Remote Control Opening Valves
2. Filling Valve
3. Strain Gage Balance Beam
4. Jet Impulse Compensation Plate
5. Temperature Rake (Thermocouples)
6. Pressure Transducer

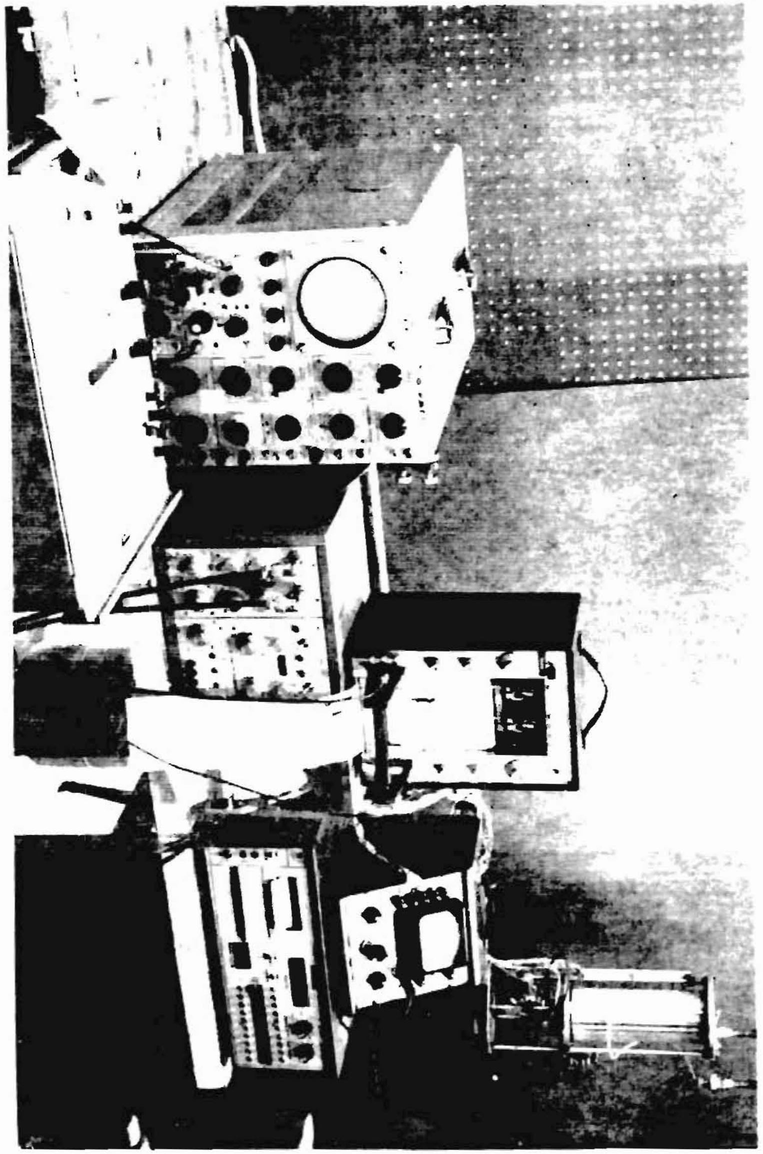

Figure 4.4 Test Arrangement for Initial Liquid Condition

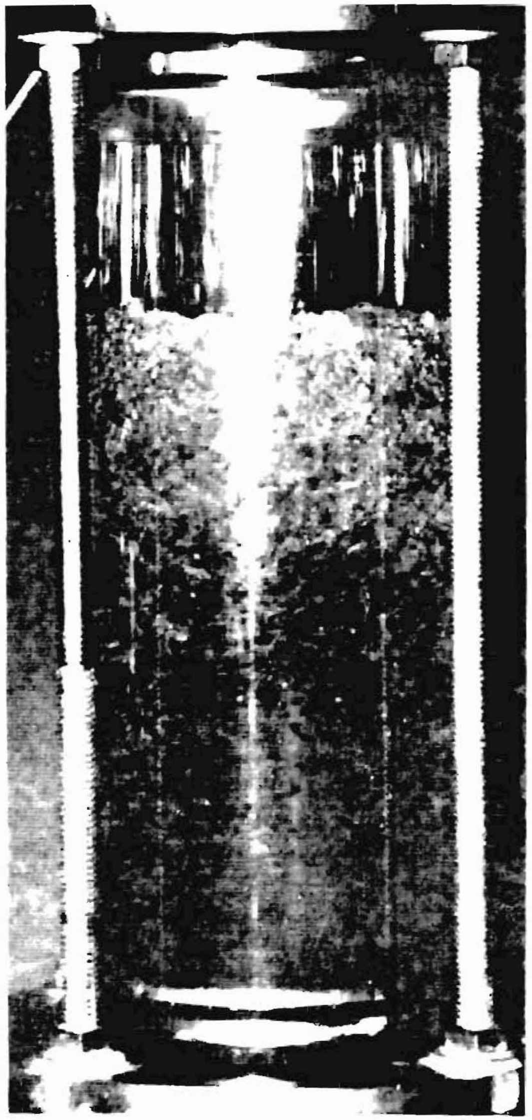

Figure 4.5 Moderate Boiling - Small Exit Orifice (medium: Freon 12)

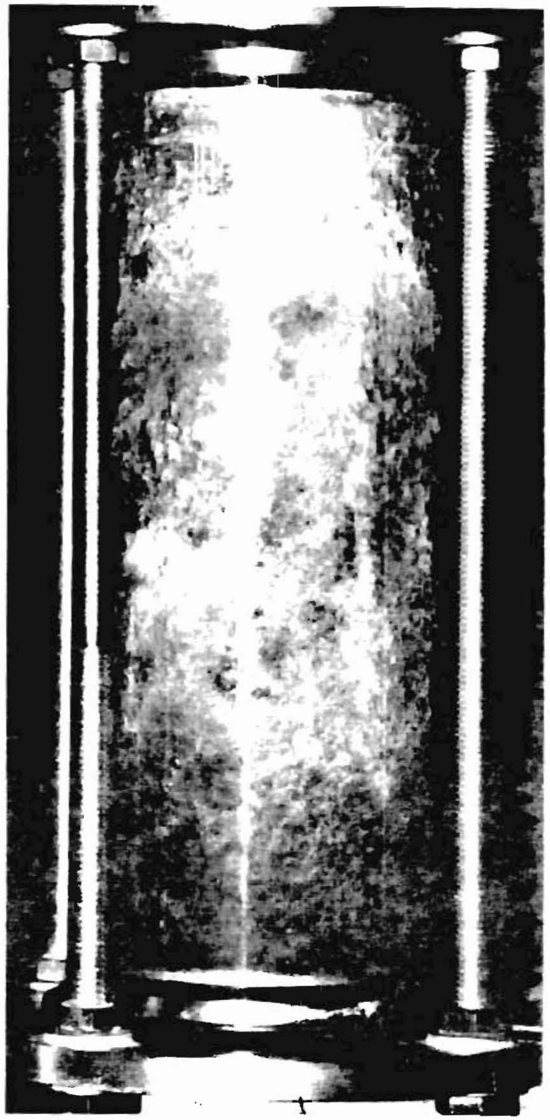

Figure 4.6 Initial Heavy Pool Boiling - Large Exit Orifice (medium: Freon 12)

Figure 4.7 Continued Heavy Pool Boiling - Large Exit Orifice (medium: Freon 12)

Figure 4.8 Exit Jet During Blow-Down (medium: Freon 12; Initial Vapor Condition)

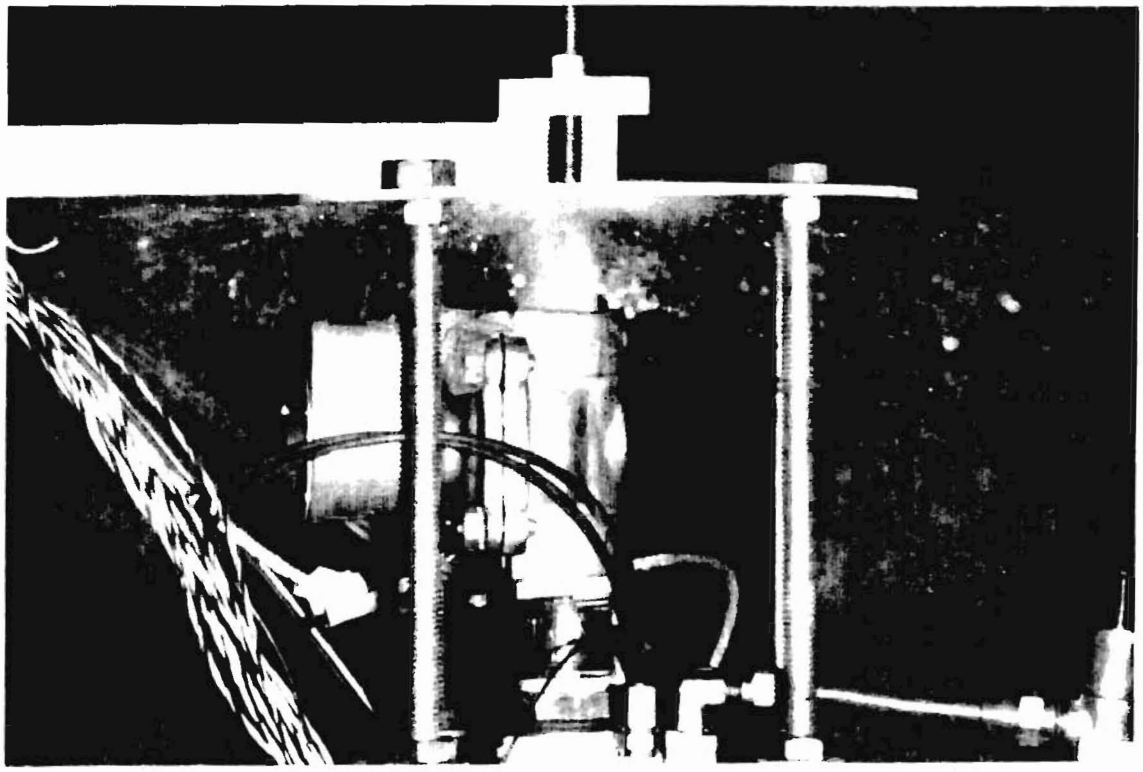

Figure 4.9 Exit Jet During Blow-Down (medium: Freon 12; Initial Vapor Condition)

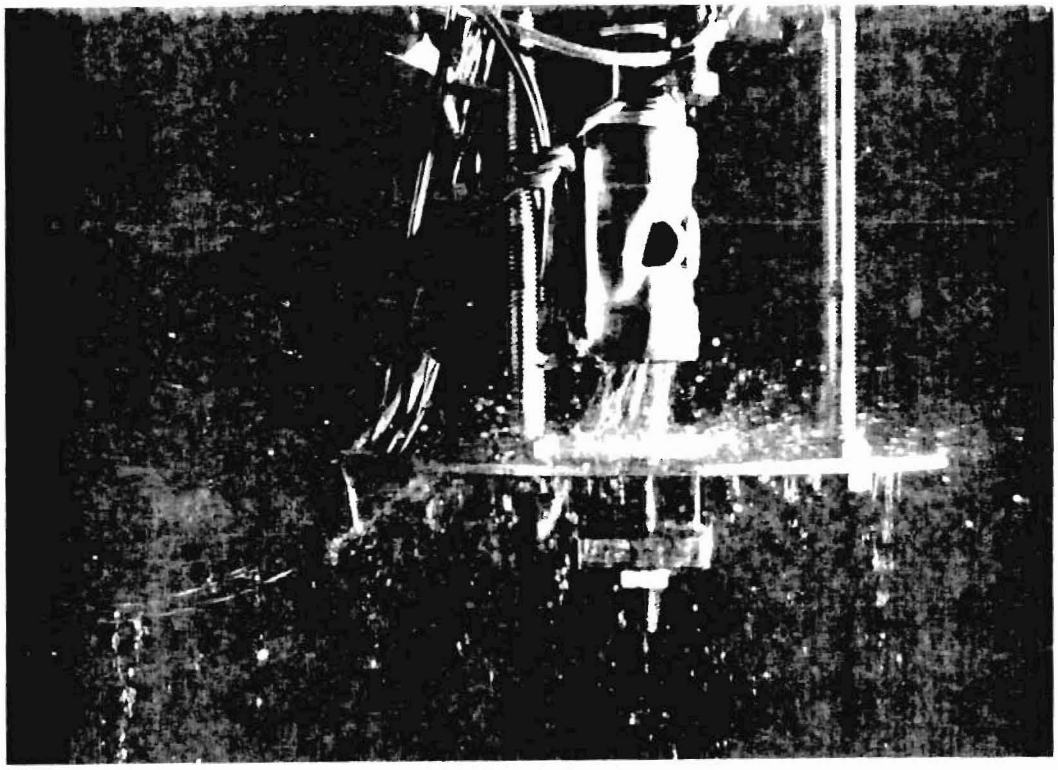

Figure 4.10 Exit Jet During Blow-Down (medium: Freon 12; Initial Liquid Condition)

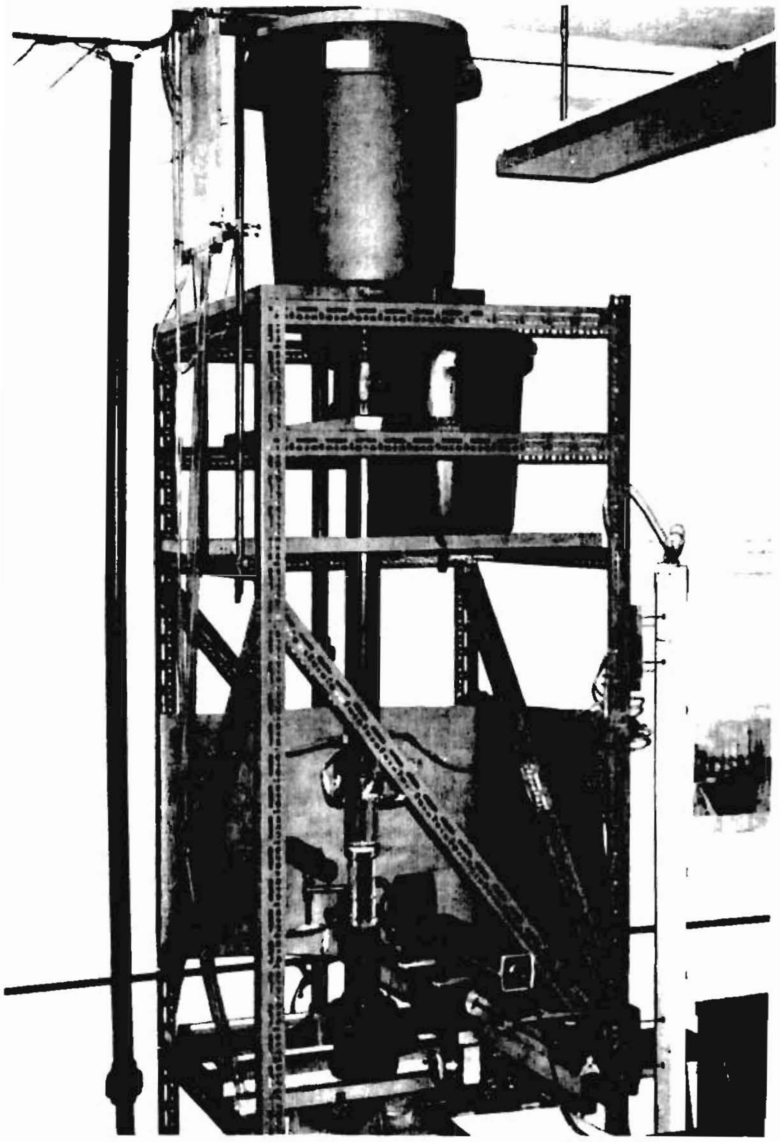

Figure 4.11 Overview of Bubble and Slug Flow Tunnel

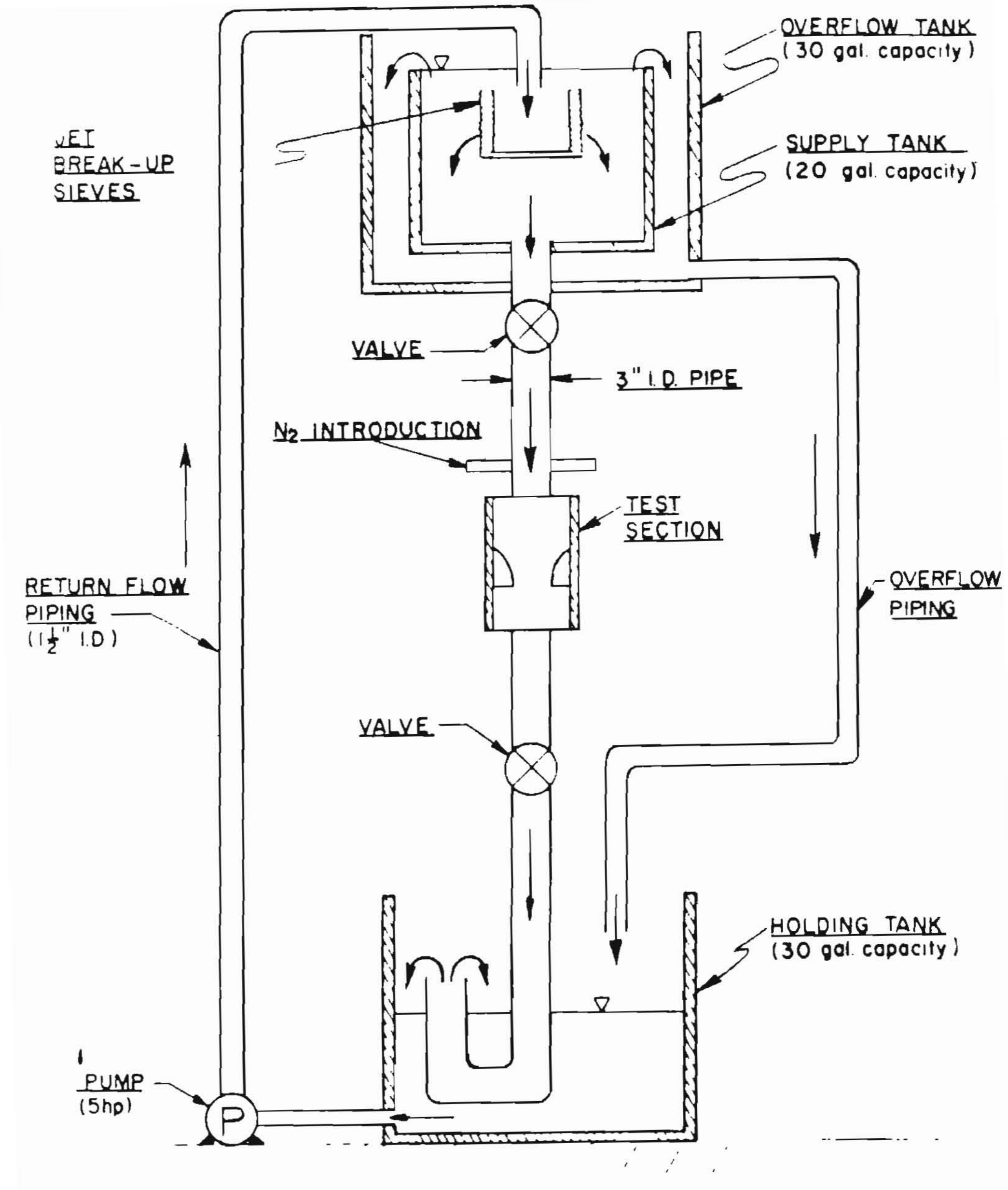

Figure 4.12 Schematic of Bubble and Flug Flow Tunnel

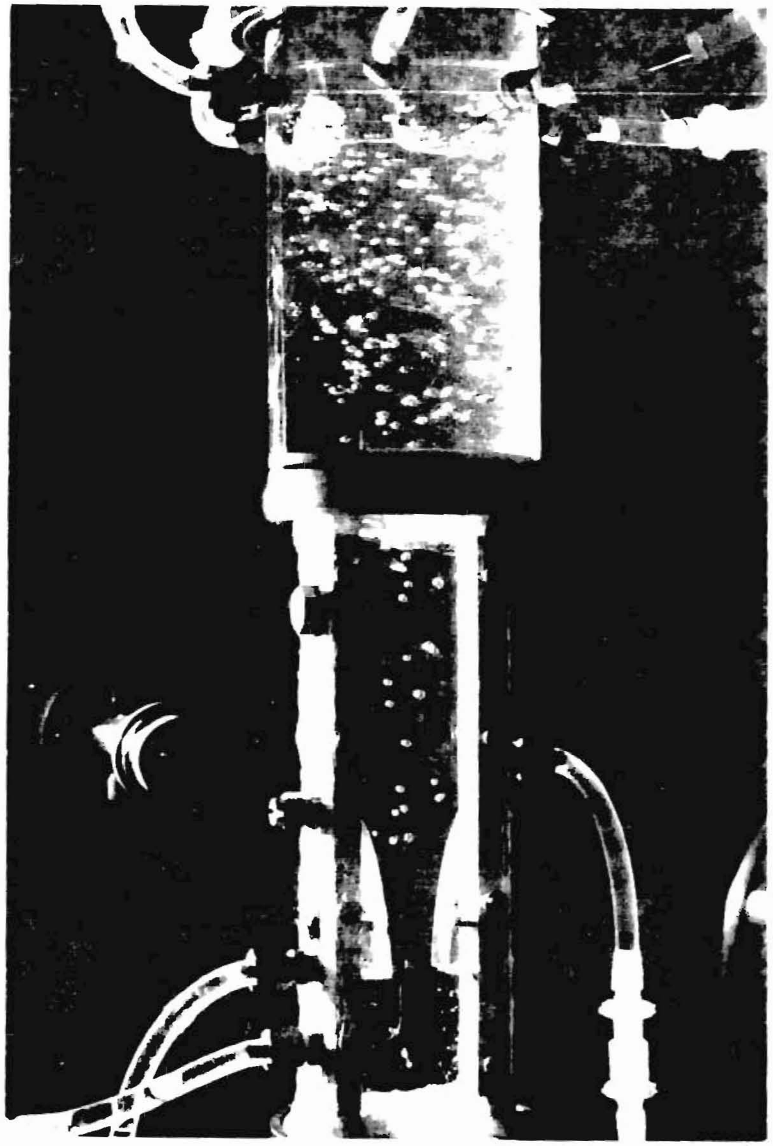

Figure 4-13a. Close-Up View of Test Section - Low Bubble Density

Figure 4-13b. Close-Up View of Test Section - High Bubble Density

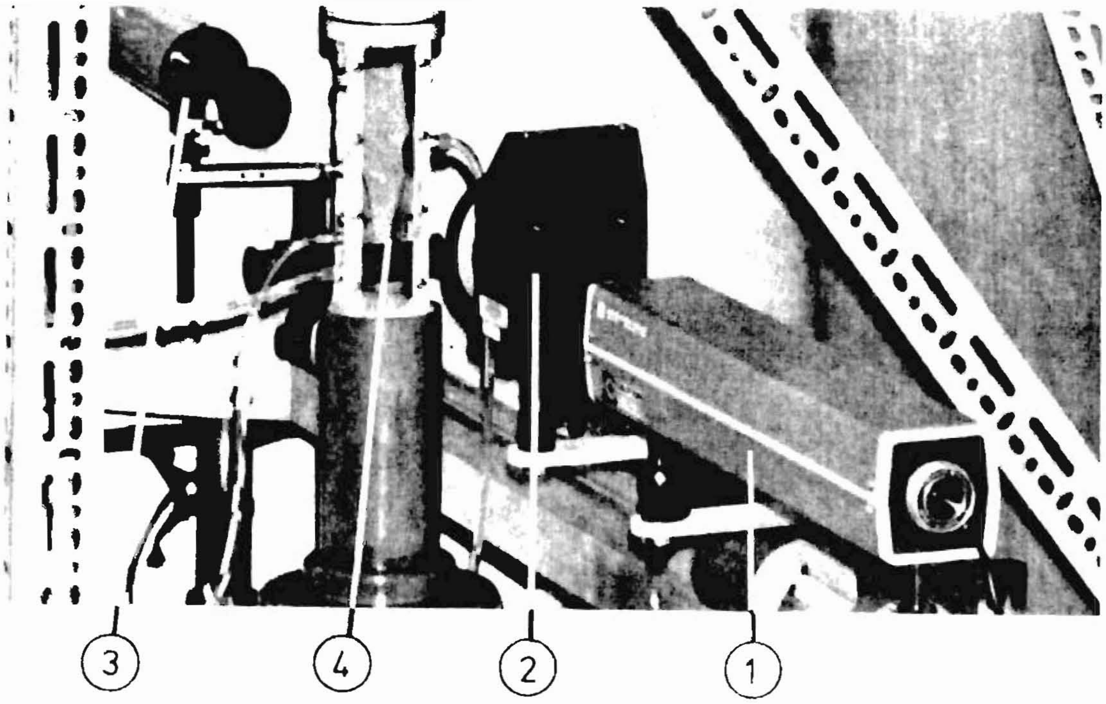

Figure 4.14 Test Section with Laser-Doppler Anemometer

1. 5 mw He-Ne Laser
2. Optical Unit and Beam Splitter
3. Photomultiplier with Receiving Optics
4. Test Section

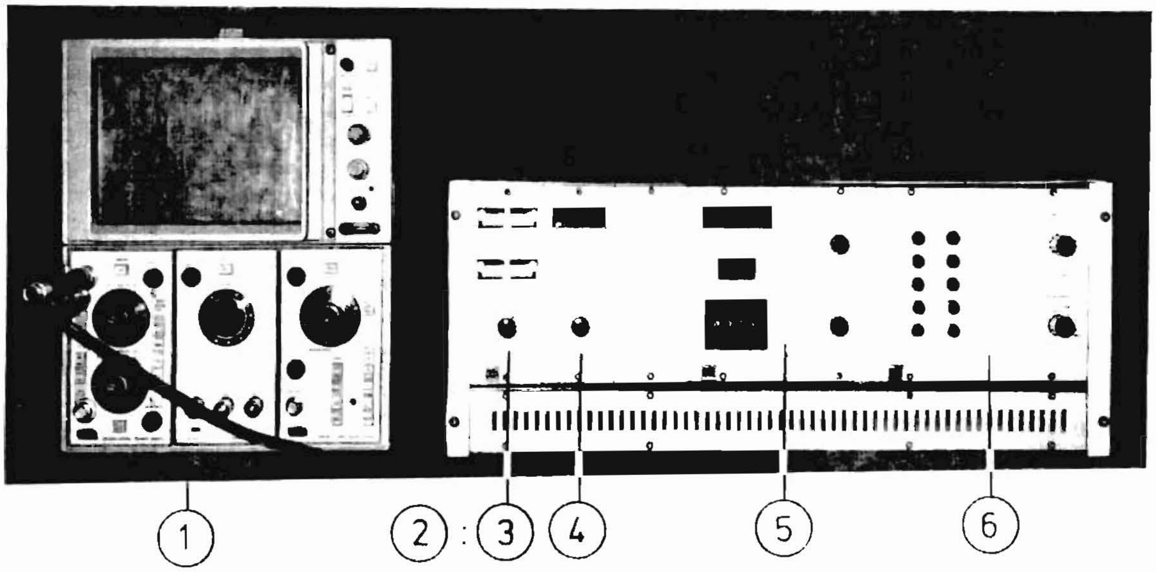

Figure 4.15 Laser-Doppler Processor Assembly

1. Oscilloscope (for burst analysis)
2. LDA Counter Processor
3. High Voltage Power Supply Module for Photomultiplier
4. Data Rate Module
5. Mean Velocity Computer Module
6. Filter and Amplifier Module for Data Processing

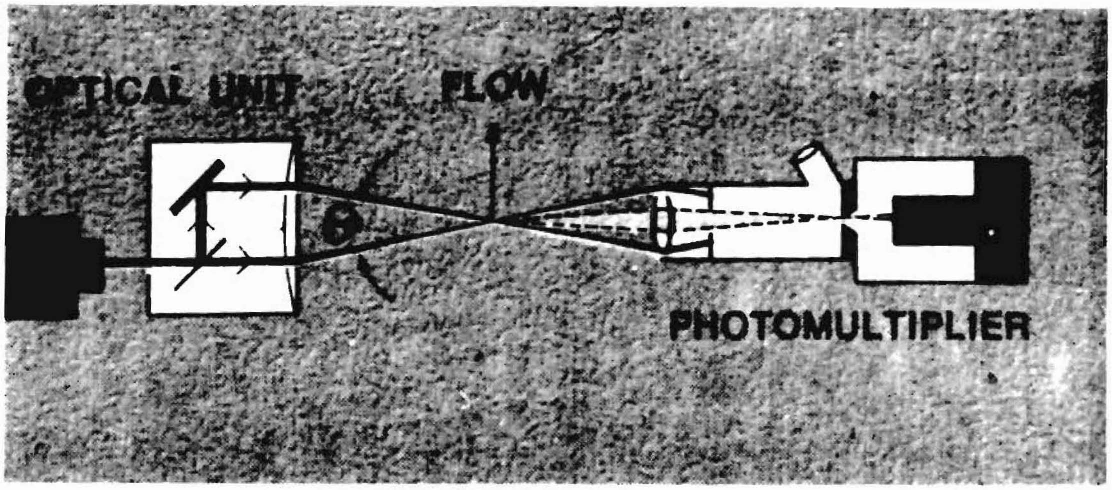

Figure 4.16 Schematic of Laser Optics

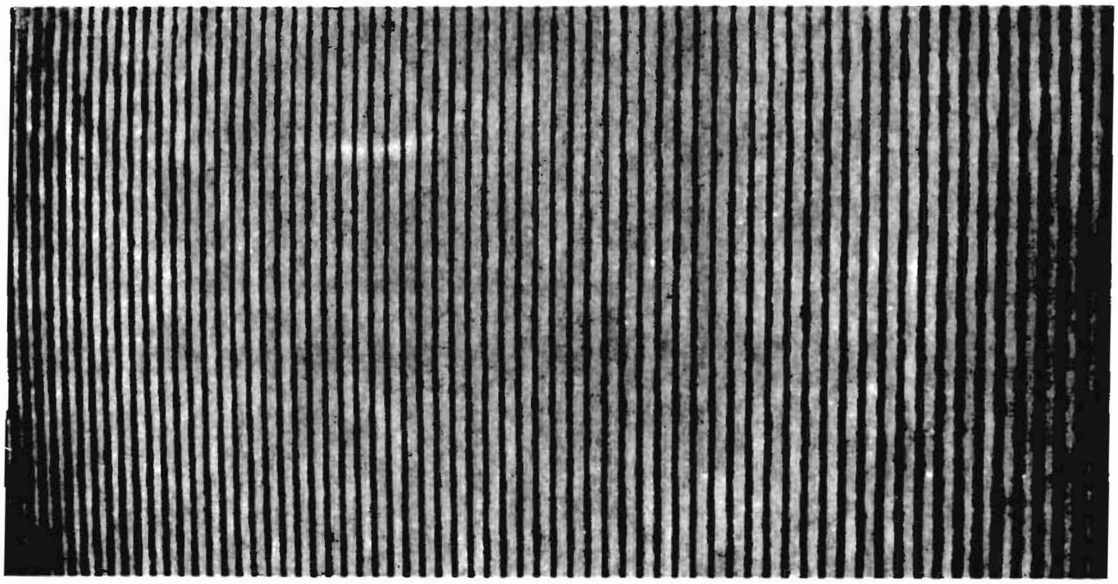

Figure 4.17 Typical Fringe Pattern

V. Bench Test Results of Flow Visualization Experiments

In an effort to gain some understanding of the flow pattern which will exist in the safety valve during one-phase subsonic incompressible flow, some simple tests were performed using a smoke tunnel. Figures 5.1 and 5.2 are photographs of streak lines through a two-dimensional Flow Rate Measurement Nozzle section. The smoke tunnel used can be redesigned or built to a much larger scale if necessary. Figure 5.3 shows the flow pattern in a typical safety valve section at different valve openings. The present bench test served only to demonstrate the feasibility of the flow visualization technique by means of air flow and smoke. Facilities to visualize high velocity compressible flow including supersonic flow with shock waves are available and their use is anticipated.

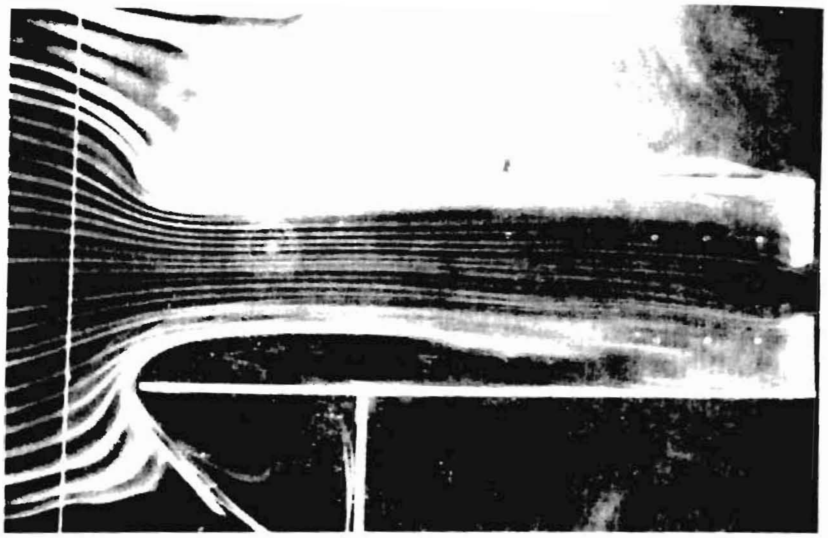

Figure 5.1 Visualization of Separation at Edge of Flow Rate Measurement Nozzle

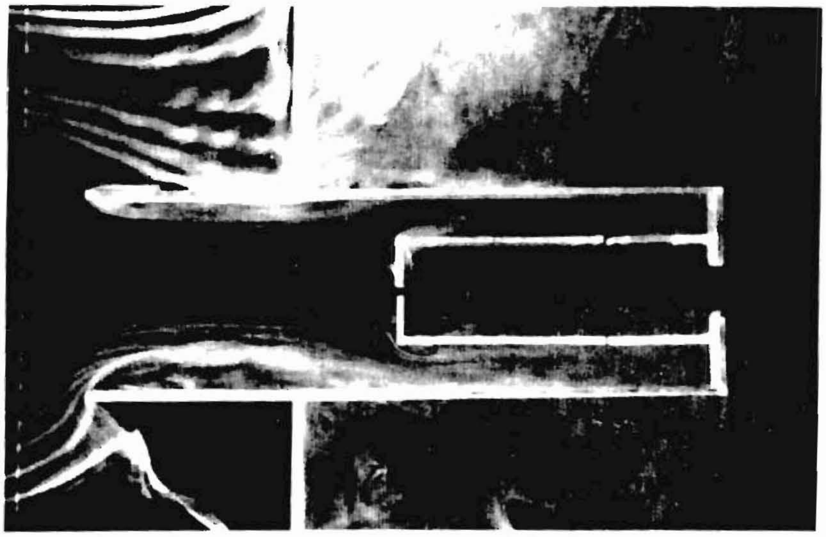

Figure 5.2 Visualization of Blocking Effect Due to Valve in Flow Rate Measurement Nozzle

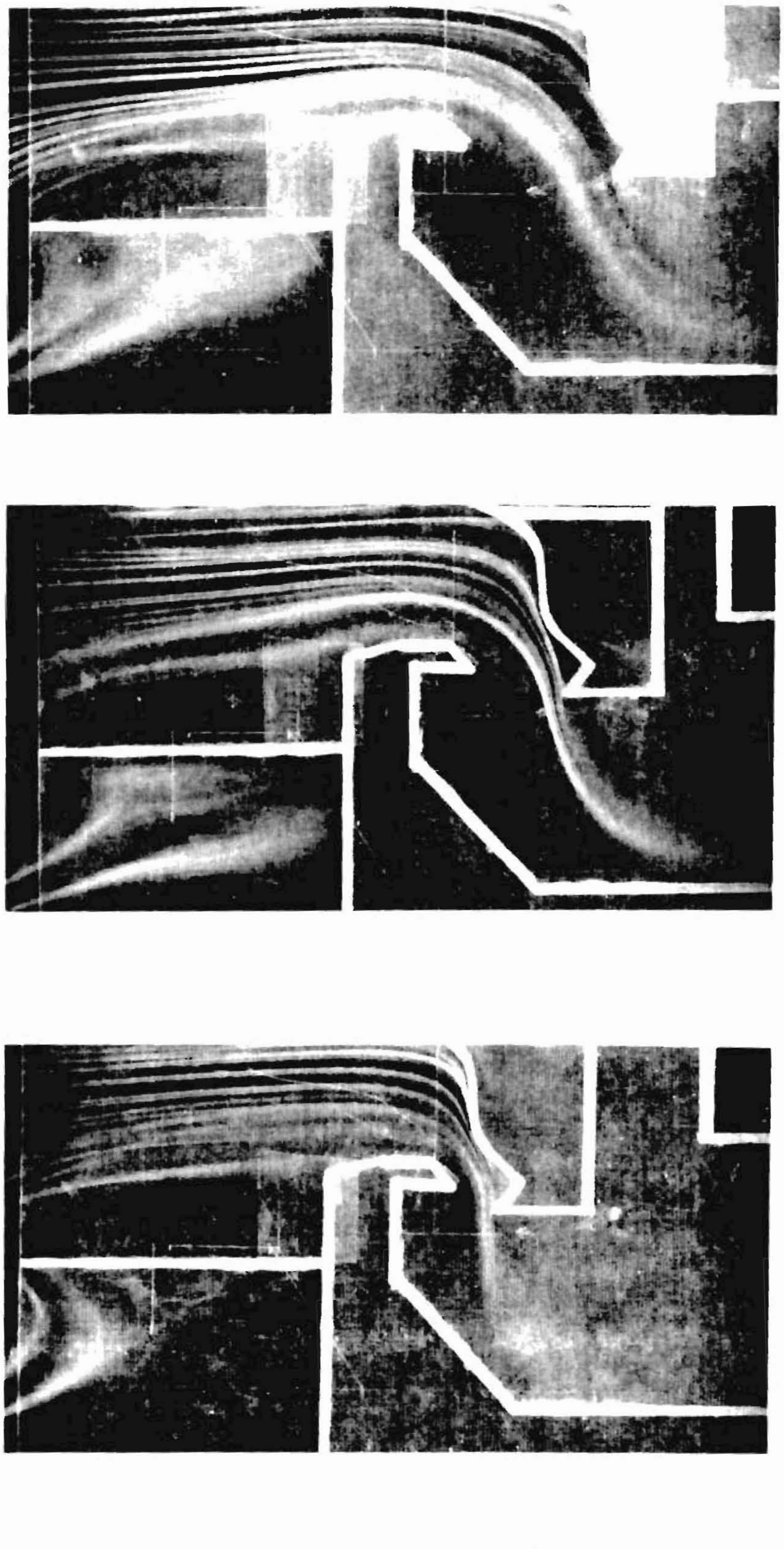

Figure 5.3 Flow Pattern in Safety Valve