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THE OHIO STATE UNIVERSITY, PH.D., 1978

TRANSITION, TURBULENCE, AND OSCILLATING FLOW

IN A PIPE

A VISUAL STUDY

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Leslie Stuart Fishler, B.S., M.S.

* * * * *

The Ohio State University

1978

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To Meredith, my FATHER

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NOMENCLATURE

A	cross sectional area of flow
C	output to input ratio of camera carriage
C_1, C_2	constants for viscosity correlation
D	pipe diameter
D_c	cylinder diameter
D_g	pitch diameter of spur gear
d	particle diameter
f	Blasius friction factor $(0.0791(N_{Re,ave})^{-0.25})$
fps	frames per second
G	gearing ratio of gearing system
g	gravitational constant
K, K_1, K_2, K_3, K_4	constants for oscillating flat plate analysis
L	entry length
L_{cam}	camera travel distance $(X_{pis} G C R_{oi} / \pi D_g)$, camera displacement
$L_{cam,max}$	maximum camera travel distance
L_{max}	maximum camera travel distance along centerline $(X_{pis} G C / \pi D_g, R_{oi} = 1)$
MgO	magnesium oxide
$N_{Re,ave}$	Reynolds number based on average velocity $(D U_{ave} / \nu)$
$N_{Re,u}$	Reynolds number based on maximum oscillatory velocity $(D U_{u,max} / \nu)$
$N_{Re,t}$	Reynolds number based on particle diameter $(d U_t / \nu)$

NOMENCLATURE (Continued)

$N_{Re,\delta}$	Reynolds number based on maximum oscillatory velocity and Stokes (boundary) layer thickness ($\delta U_{u,max}/\nu$)
$N_{Rec,ave}$	critical Reynolds number based on average velocity ($D U_{ave}/\nu$)
$N_{Rec,u}$	critical Reynolds number based on maximum oscillatory velocity ($D U_{u,max}/\nu$)
$N_{Rec,\delta}$	critical Reynolds number based on maximum oscillatory velocity and Stokes (boundary) layer thickness ($\delta U_{u,max}/\nu$)
n	number of points used in averaging
P	instantaneous pressure
$\bar{P}$	short-time average instantaneous pressure ($\frac{1}{T} \int^T P dt$)
P'	oscillatory dimensionless pressure ($P_u / \frac{1}{2} \rho U_{ave}^2$)
P_s	steady instantaneous pressure
P_u	oscillatory instantaneous pressure
p	instantaneous pressure fluctuations
R	pipe radius
R_{camz}	correlation coefficient between U_{cam} and $U_{z,ap}$ ($\overline{u_{cam} u_z} / \sqrt{u_{cam}^2 u_z^2}$)
R_{oi}	output to input ratio of Floyd Drive (X_{max1}/L_{max})
r	radial coordinate
r'	dimensionless radial coordinate (r/R)
rms	root mean square
rpm	revolutions per minute
T	characteristic period of time, period of one cycle for harmonic motion
T^*	temperature
T_c	critical value of the period

NOMENCLATURE (Continued)

TCE	trichloroethylene
t	time coordinate, settling time (x/U_t)
t'	dimensionless time coordinate (ωt)
U	instantaneous velocity in the flow direction
$\bar{U}$	short-time average instantaneous velocity ($\frac{1}{T} \int^T U dt$)
U'	oscillatory dimensionless velocity (U_u/U_{ave})
U ⁺	dimensionless velocity ($U_{u,max1}/U^*$)
U*	friction velocity ($U_{ave}(\epsilon/2)^{0.5}$)
U _{amp}	amplitude parameter ($U_{u,max}/U_{ave}$)
U _{ave}	average velocity ($\frac{1}{AT} \int^T \int^A U dA dt$)
U _{cam}	camera velocity
$\bar{U}_{cam}$	average camera velocity ($\Sigma U_{cam}/n$)
U _{cam,max}	maximum camera velocity ($\pi L_{cam}/T$)
U _r	radial particle velocity
$\bar{U}_r$	average radial particle velocity ($\Sigma U_r/n$)
U _s	instantaneous steady velocity
U _t	terminal settling velocity of a particle ($d^2 (\rho_{MgO} - \rho_{TCE})g/18\mu_{TCE}$)
U _u	instantaneous oscillatory velocity
U _{u,max}	maximum oscillatory velocity ($\pi X_{max}/T$)
U _{u,max1}	amplitude of the oscillatory velocity at radial positions
U _{vortex}	convective velocity of the vortex ($\Sigma U_z/n$)
U _z	actual axial particle velocity ($U_{z,ap} + U_{cam}$)
U _{z,ap}	apparent axial particle velocity

NOMENCLATURE (Continued)

$\bar{U}_{z,ap}$	average apparent axial particle velocity ($\Sigma U_{z,ap}/n$)
$U_{z,vortex}$	axial particle velocity in vortex coordinates ($U_z - U_{vortex}$)
u_{cam}, u_r, u_z	deviations from $\bar{U}_{cam}, \bar{U}_r$, and $\bar{U}_{z,ap}$ ($U_{cam} - \bar{U}_{cam}, U_r - \bar{U}_r, U_{z,ap} - \bar{U}_{z,ap}$)
u'_{cam}, u'_r, u'_z	rms velocities ($\sqrt{\Sigma u_{cam}^2/n}, \sqrt{\Sigma u_r^2/n}, \sqrt{\Sigma u_z^2/n}$)
u_z, u_r, u_θ, u	instantaneous velocity fluctuations
X	displacement
X_{max}	fluid displacement at the centerline in half a cycle ($X_{pis} D_c^2/D^2$)
X_{maxl}	fluid displacement at radial positions in half a cycle
X_{pis}	piston stroke length, scotch yoke displacement
$X_{pis,max}$	selected value of piston stroke length for design
$X_r, X_{z,ap}$	particle displacement in the radial and apparent axial directions
X_z	particle displacement in the axial direction ($X_{z,ap} + L_{cam}$)
$X_{z,vortex}$	axial particle displacement in vortex coordinates ($\int U_{z,vortex} dt$)
x	settling height of a particle
y	radial coordinate from wall ($R - r$)
y^+	dimensionless radial coordinate from wall ($y U^*/\nu$)
z	axial coordinate
z'	dimensionless axial coordinate (z/R)
α	frequency parameter ($R\sqrt{\omega/\nu}$)
α_c	critical value of frequency parameter
δ	Stokes (boundary) layer thickness ($K\sqrt{2\nu/\omega}$)

NOMENCLATURE (Continued)

θ	azimuthal. coordinate
μ	fluid viscosity
ν	fluid kinematic viscosity (μ/ρ)
ρ	density
ω	angular frequency ($2\pi/T$)

ABSTRACT

Transitional and turbulent oscillatory flow in a pipe was investigated using a flow visualization technique to establish the existence of coherent flow structures and to describe them. The flow visualization technique involved suspending tracer particles in a fluid to mark the fluid motions and taking high speed motion pictures of the fluid in motion. The geometry used was a rigid, circular, straight pipe of constant cross section with enough entry length on either side to insure fully developed oscillatory flow. The simple harmonic motion of a scotch yoke and flywheel linked to a piston and cylinder provided the flow driving force. The camera was convected along with the flow by attaching it through a gearing system to the scotch yoke. A variable speed reducer allowed the camera velocity to be matched to the fluid velocity at positions near the pipe wall.

Theoretically, two similarity parameters, the Reynolds number based on peak velocity and the frequency parameter, are the governing nondimensional parameters for oscillatory flow. Values of the peak Reynolds number from 7200 to 22000 and the frequency parameter from 6.65 to 16.40 were investigated. Sets of runs were made with the peak Reynolds number held constant and the frequency parameter variable. The same procedure was used for constant frequency parameter and variable peak Reynolds number.

There were two major results of these experiments. First, coherent structures for transitional and turbulent oscillatory flow were shown to exist. Secondly, turbulence according to the coherent flow structures depended on the peak Reynolds number and the frequency parameter. The trends predicted from the coherent flow structures agreed with both theory and comparable results from the literature.

The coherent structures of transitional and turbulent oscillatory flow were a series of deterministic events which occurred randomly in space. However, the flow structures exhibited time dependence, occurring only during decelerated flow. Five events called retardation, influx, excitation-rotation, discharge, and purge (possibly a relaminarization) were postulated. Three of the events, influx, excitation, and discharge, were characterized by large radial motions of the tracer particles. These three events and especially the excitation and discharge are believed to play an important role in the generation of turbulence. The rotation event is believed to be important to the laminar-turbulent transition process in oscillatory flow. The oscillatory transitional and turbulent flow structures were found to be very similar to the previously determined steady turbulent flow structures. However, different names were chosen for the oscillatory events to avoid suggesting the same mechanism must necessarily apply.

Using the transitional and turbulent oscillatory flow structures as a measure of the degree of turbulence, it was found that turbulence decreased with increasing frequency parameter and increased with increasing peak Reynolds number. For some combinations of the similarity parameters, no flow structures were observed. A range of values of the

critical Reynolds number based on peak velocity and Stokes (boundary) layer thickness was calculated using the existence of flow structures as the criterion of turbulence. The values from this study agreed with other values from the literature and point out that the oscillatory flow structures are a good indicator of transition to turbulence.

On the basis of this study, recommendations for further investigation of the coherent oscillatory flow structures by visual and hot-film anemometry techniques are suggested. The similarity parameters should be studied over a wider range of values. Complexities such as entrance effects and mean flow should also be examined for their effect on the transitional and turbulent oscillatory flow structures. The excitation and discharge events should be studied carefully to see if they contribute to turbulence generation.

INTRODUCTION

Since the discovery by Osborne Reynolds of the transition from laminar to turbulent flow, there have been many theoretical and experimental investigations of the laminar-turbulent transition process. Fully turbulent flow has also been a subject of considerable interest. However, most of the work on the transition and turbulence problems has been for steady flow. Steady flow is defined as a flow without time dependence. For example, a plot of instantaneous velocity at a point versus time for both laminar and turbulent flows is shown in figure 1a. In turbulent flow, when the short-time average velocity, $\bar{U}$ (defined later in this section), is independent of time, this flow is known as stationary turbulence.

Recently, there has been interest, both theoretical and experimental, in unsteady flows in the transitional and turbulent states. Unsteady flows can be divided into two cases with respect to instantaneous velocity at a point. The first case is pulsatile or pulsating flow (figure 1b) where the flow consists of a velocity component oscillating with time (U_u) superposed on a steady velocity component (U_g). The other case is oscillating or oscillatory flow (figure 1c) where the velocity varies with time and the steady velocity is zero. Oscillating flow is therefore a special case of pulsatile flow. Pulsatile flows can be either laminar, transitional, or turbulent. For turbulent

Figure 1. Instantaneous velocity at a point versus time. (a) Steady flow. (b) Pulsatile flow. (c) Oscillating flow. (For turbulent flow in (b) and (c), $U = \bar{U}$, $U_s = \bar{U}_s$, and $U_u = \bar{U}_u$.)

pulsatile flow, the instantaneous velocity at a point, U , has random fluctuations when measured over a period of time. This is not demonstrated in figures 1b or 1c. However, short-time averaged pulsatile flow may be represented in figures 1b and 1c by substituting $\bar{U}$ for U , $\bar{U}_s$ for U_s , and $\bar{U}_u$ for U_u . Short-time averaging eliminates the fluctuations associated with turbulent flow. If the oscillating velocity component continues to repeat itself over a specified period of time, the flow is called periodic. The type of oscillating turbulent flow studied in this investigation is illustrated in figure 2. Turbulence occurred only in the decelerated part of the flow cycle.

In turbulent flow, random fluctuations occur in both the velocity and other properties of the flow and these random fluctuations have a time scale. The oscillating component of a pulsatile flow also has a time scale associated with it. This necessitates discussing averaging procedures which apply to pulsatile and turbulent flows. The averaging procedures are defined with respect to velocity, but they also apply to other variables.

Short-time averaging is defined as

$$\bar{U} = \frac{1}{T} \int^T U \, dt \quad (1)$$

where the instantaneous velocity at a point in the flow direction is

$$U = \bar{U} + u, \quad (2)$$

t is the time coordinate, T is a characteristic time of averaging, and u is the instantaneous velocity fluctuation in the direction of U . For turbulent pulsatile flow, T is chosen large enough to average out the

Figure 2. Illustration of the type of oscillating turbulent flow studied in this investigation.

random fluctuations characteristic of turbulent flow, but small enough not to affect the oscillating component. Therefore, $\bar{U}$ is a function of time. This type of averaging is based on the assumption that the time scale of the turbulent fluctuations is much smaller than the time scale associated with the oscillating component of the flow.

If there are any random fluctuations of the same order of magnitude in time scale as the oscillating component, then short time averaging cannot be used. In such a case an ensemble average must be used. However, if the oscillating component is nonperiodic, then the random fluctuations due to turbulence and the oscillating component are difficult to distinguish. The three dimensionality of turbulence is one means to distinguish between the two. An ensemble average of a point velocity can be obtained by measuring the period of the oscillating component and then measuring the velocity over many experiments at the same point in the flow cycle. From these measurements, the average velocity of the point in space and time and the random turbulent fluctuations can be calculated. This type of averaging will not be used in this work.

The cross sectional average velocity is defined as

$$U_{ave} = \frac{1}{AT} \int^T \int^A U \, dA \, dt \quad (3)$$

where A is the cross sectional area in the direction of flow. In this situation, T is chosen large enough to average out all time-dependent variations. Averages of this type can also be taken with respect to time and cross sectional area individually.

One reason for the interest in pulsatile transitional and turbulent flows is the possible application to blood flow in the large

arteries. Evidence is available which shows that transition to turbulence in the large arteries occurs under diseased conditions and sometimes under normal circumstances in humans and large animals. Other work has shown that turbulent flow in the large arteries is deleterious. Another biological example of turbulence is respiratory flow in the trachea. Some other applications for transitional and turbulent pulsatile flow of practical importance are the enhancement of heat and mass transfer over that in a corresponding steady flow, the design of pumps and other process equipment with transient flow patterns, and the startup, shutdown, and change of variables of processes.

Pulsatile flows and especially flows related to arterial flow are very complex and therefore difficult to model analytically. Some of the phenomena which must be accounted for in arterial flow are, curvature, branching, and taper of the vessel; wall properties; fluid properties; and entrance effects. For laminar pulsatile flow, the problem is manageable. For turbulent pulsatile flow, any analytical analysis becomes extremely difficult without experimental knowledge of some of the properties of the flow.

An experimental study of oscillatory transitional and turbulent flow was chosen as the research topic of this dissertation. The objective was to obtain a better physical understanding of the phenomena occurring in oscillatory flow. The method chosen to investigate the flow to establish the existence of coherent flow structures was a flow visualization technique. This technique is identical to the technique used in previous flow visualization studies of steady turbulent flow done at The Ohio State University.

The experimental procedure was to suspend tracer particles in a fluid to mark the fluid motions but not to disturb them, to illuminate the fluid and particles, and to take high speed motion pictures of the fluid motions from a convective viewpoint. The wall region of the pipe was the area of interest. The geometry used was a straight, rigid, circular pipe of constant cross section with enough entry length on either side to allow for fully developed flow. The fluid was Newtonian. The flow was oscillatory and driven by the simple harmonic motion of a piston and cylinder.

From theoretical considerations, it can be demonstrated that three similarity parameters, the average Reynolds number ($N_{Re,ave}$), the frequency parameter (α), and the amplitude parameter (U_{amp}), are sufficient to characterize pulsatile flow in a pipe. These three similarity parameters are defined as

$$N_{Re,ave} = D U_{ave}/\nu, \quad (4)$$

$$\alpha = R \sqrt{\omega/\nu}, \quad (5)$$

and

$$U_{amp} = U_{u,max}/U_{ave} \quad (6)$$

where D is the pipe diameter, R is the pipe radius, ν is the kinematic viscosity of the fluid, ω is the angular frequency, and $U_{u,max}$ is the maximum oscillatory velocity. For oscillating flow in a pipe, only two similarity parameters are necessary. They were selected as peak Reynolds number ($N_{Re,u}$) defined as

$$N_{Re,u} = D U_{u,max}/\nu \quad (7)$$

and α . It should be noted that for oscillating flow the Reynolds number is usually based on $U_{u,max}$ since U_{ave} is zero. Another commonly encountered Reynolds number for oscillatory flow is based on Stokes (boundary) layer thickness (δ) and is defined as

$$N_{Re,\delta} = \delta U_{u,max}/\nu . \quad (8)$$

In this study, the values of $N_{Re,u}$ and α were varied independently. Reynolds numbers from $N_{Re,u} \approx 7200$ –22000 and frequency parameters from $\alpha \approx 6.60$ –16.60 were studied. Three values of $N_{Re,u}$ (7200, 11000, and 22000) were held constant while α was varied, and two values of α (9.50 and 11.60) were held constant while $N_{Re,u}$ was varied. The sets of values of the similarity parameters studied included combinations of $N_{Re,u}$ and α in the normal human physiological range, the range where transition to turbulence occurs, and the quasi-steady turbulent regime (a model for turbulent pulsatile flow) as documented in the literature.

In the range of similarity parameters studied, transition to turbulence for oscillatory flow occurred during the decelerating part of the flow cycle, and relaminarization occurred with flow acceleration (see figure 2). This fact has been demonstrated by many other investigators and is well documented in the literature. The transition to turbulence during flow deceleration was carefully studied in the visual analysis.

Coherent flow structures for transitional and turbulent oscillatory flow are presented. Coherent flow structures are randomly occurring but deterministic sequences of events observed in the flow. The oscillatory flow structures are compared with other results from

the literature for pulsatile and oscillatory flow. The oscillatory flow structures are also compared with the previously determined steady turbulent flow structures. The variation of turbulence according to the flow structures with $N_{Re,u}$ and α is discussed. A range of values of the critical Reynolds number, $N_{Rec,\delta}$, was determined from the flow structures, and compared with other experimentally determined values for oscillatory pipe flow.

In the next chapter, the literature relevant to transitional and turbulent pulsatile flow is presented. A short theoretical chapter is included demonstrating the similarity parameter dependence for pulsatile and oscillatory flows. The experimental program is outlined in the ensuing chapter. In the following two chapters, the experimental results and comparisons of the results with previous work from the literature are presented. Conclusions and recommendations are offered in the final two chapters. The appendix contains some supplementary material on the design of the experimental equipment.

LITERATURE REVIEW

In this section the work of previous investigators is discussed. It will be established that transitional and turbulent pulsatile flows do exist in vivo and that these flows may be deleterious. Basic concepts pertaining to the analytical solution of laminar and turbulent flow problems, and some laminar pulsatile flow models which are related to arterial flow are presented in the Mathematical Analyses section. This is done to show that transitional and turbulent pulsatile flow and arterial flow are very complex, and experimental work is necessary to better understand these flows. Transition phenomena are presented with a discussion of the research into critical Reynolds numbers for pulsatile flow. Three types of critical Reynolds numbers are discussed: $N_{Rec,ave}$, $N_{Rec,u}$, and $N_{Rec,\delta}$. Other effects pertaining to transition, such as relaminarization, are also reviewed. Work on the modeling of turbulent pulsatile flow and the experimental verification of the models is presented. A critical value of α where the flow changes from a quasi-steady form is shown to exist. Turbulent pulsating boundary layers are also briefly discussed. Finally, the few previous visual studies for transitional and turbulent pulsatile flow are discussed. A brief introduction to the concept of coherent structures in turbulence is presented based on steady flow visual studies.

In Vivo Turbulence

Since a very important application of transitional and turbulent pulsatile flow is related to blood flow in the large arteries, it is only fair to ask the question: do these kinds of flows truly exist in either the normal human physiological state or in the diseased state? This is a difficult question to answer conclusively for two reasons. First, it is unlikely that many healthy human beings would subject themselves to experimentation. Secondly, the instrumentation for detecting turbulence in the large arteries was not available until the rather recent development and application of hot-film anemometer systems to blood flows (37, 65, 67, 68). Hot-film anemometers made the accurate measurement of point velocities in the large arteries possible. Still most in vivo data has been taken on experimental animals and diseased humans.

The first in vivo indication of turbulence in a blood flow was done by McDonald (42) using a high speed cinematography technique. This study showed a breakdown of laminar flow before peak velocity in the aorta of a rabbit. Lynch and Bove (41) and Ohlsson (53) also observed what is believed to be turbulence in aortic flows using high speed cineradiography techniques.

With the use of hot-film anemometry in the study of arterial flows, a better understanding of the qualitative and quantitative nature of turbulence in these flows has been obtained. A method of characterizing the flow from velocity waveforms taken with a hot-film anemometer was proposed by Nerem and Seed (49). They divided the velocity waveforms

into three categories, undisturbed, disturbed, and highly disturbed, based on the observation of high frequency components in the waveform. These categories are thought to be representative of laminar, transitional, and turbulent flows respectively. The measurement of point velocities using hot-film anemometry also enabled quantitative information on turbulence in arterial flows to be obtained. Quantities related to the turbulence level such as the turbulence intensity can be calculated from point velocity measurements. The remainder of the studies discussed in this section on in vivo turbulence utilized hot-film anemometry techniques.

In in vivo experiments on normal animals (dogs and pigs), turbulent flow of blood in the large arteries was the exception rather than the rule (19, 37, 65, 69). However, turbulence was observed in some studies (37, 69). In experiments by Nerem and Seed (49) on small dogs where the heart rate and peak velocity were controlled by drugs or nerve stimulation, there were many instances of turbulent flow in the large arteries. Other experiments by Nerem, Rumberger, Gross, Hamlin, and Geiger (48) on conscious and unconscious horses also showed evidence of turbulence in blood flows. Evidence has been found which shows that turbulence does exist in the human circulation (64, 65, 75), but most of the patients studied had some form of heart disease. However, turbulence was observed in one normal patient during peak flow (75).

These in vivo studies and the extrapolations that can be drawn from them show that turbulence occurs in animal and human arterial flows for the diseased state and turbulence may be expected to occur at peak velocity for the normal state. However, other reasons exist for the

study of transition and turbulence in pulsatile flow with regard to arterial flow. Turbulent blood flow has been associated with heart murmurs (59) and thrombus formation (74). The high rate of shear in a turbulent flow may cause damage to blood vessel walls (20). Turbulence has also been implicated in atherosclerosis (61).

Mathematical Analyses

In this section mathematical analyses pertinent to laminar, pulsatile flow and related to arterial flow are discussed. Theories for transitional and turbulent pulsatile flow are discussed in the next two sections, but some basic concepts which relate to the difficulty of their analytical solutions are discussed here. The purpose is to show that pulsatile and arterial flow phenomena of practical importance are very complex and that experiments are needed to better understand these flows especially in the transitional and turbulent states.

For laminar and transitional flows exact analytical models are possible if solutions to the governing differential equations can be found. With judicious assumptions this has been achieved, even if only by numerical methods, but for the more complex flow phenomena important effects are neglected. However, with turbulent flow exact solutions are not possible because the averaging procedures involved generate sets of equations with more unknowns than equations. Simple experiments are needed to determine cause and effect relationships and to provide a data base for the empirical equations necessary to close the set of equations and unknowns for pulsatile flow in the turbulent state. Experiments are also needed for the laminar and transitional states to confirm the theory and to investigate more complex flow situations.

There have been many analytical solutions of the Navier-Stokes equations for laminar, Newtonian, incompressible, pulsatile flow in a rigid tube (23, 24, 30, 36, 58, 71, 77, 80, 82, 83, among others). These solutions have been corroborated experimentally by Linford and Ryan (38) and Denison, Stevenson, and Fox (18). The solutions of Uchida (80) and Womersley (83) are directly applicable to arterial flows. Uchida (80) assumed that the pressure gradient and the velocity are harmonic functions in time, and used a separation of variables technique to solve the Navier-Stokes equations for the velocity profile for each harmonic. This is useful when experimental pressure gradient data is available.

For an improved mathematical model of arterial flow (or pulsatile flow with more complexities), other effects must be taken into account. These effects include curvature, taper, and branching of the tube; wall properties; and entrance effects. One analysis which includes some of these effects and also agrees with related experiments was proposed by Womersley (84). Womersley assumed in his analysis that the wall is a straight, Hookian, isotropic, tethered tube, and the fluid is Newtonian, incompressible, and in laminar flow. Womersley linearized the Navier-Stokes and wall displacement equations to obtain a solution. If the flow is assumed one-dimensional, a nonlinear solution is achievable. Such a nonlinear solution was developed by Anliker, Rockwell, and Ogden (1) and includes the effects of branching and taper. Entry effects have been investigated analytically for rigid tubes by Chang and Atabek (7) and for elastic tubes by Kuchar and Ostrach (35). The model

of Kuchar and Ostrach (35) degenerates into that of Womersley (84) for long tubes. Curvature effects have been studied by Smith (73).

These mathematical models are fairly complicated to use and no single model which takes into account all the effects encountered in arterial flows can be solved analytically at present. Although much has been done analytically (and corroborated experimentally) to understand laminar, pulsatile flow, for turbulent flow one cannot proceed without experimental data to close the set of equations and unknowns which govern such flows. It is also necessary to have a qualitative physical understanding of what is occurring in transitional and turbulent pulsatile flow and in what range of the similarity parameters important effects occur. One means of accomplishing these ends is a flow visualization study.

Transitional Pulsatile Flow Studies

From solutions of the Navier-Stokes equations for laminar, pulsatile flow in a rigid tube, for example (22, 80), it has been shown that the dimensionless velocity profile is a function of two similarity parameters: $N_{Re,ave} = \frac{DU_{ave}}{\nu}$ and $\alpha = R\sqrt{\omega/\nu}$. This analysis can be extended to transitional flow and the question asked: what controls $N_{Rec,ave}$? It was theorized by Gilbrech and Combs (22) that $N_{Rec,ave}$ is a function of α and $U_{amp} = U_{u,max}/U_{ave}$ in contrast to steady flow where it is just a constant. This is the presently accepted theory. Furthermore, the effect of frequency is considered more important, especially at low amplitude oscillations.

The first experimental attempt at obtaining $N_{Rec,ave}$ for pulsatile flow in a tube was done by Binnie (3) using a double refraction method. Kastner and Shih (32) used a pressure drop versus flow rate technique to get $N_{Rec,ave}$ for a pulsating channel flow. Hale, McDonald, and Womersley (25) postulated an effective $N_{Re,ave}$ for pulsatile flow which corresponds to a steady flow $N_{Re,ave}$ with the same wall shear rate and used the steady flow criterion for transition. Darling (15) studied $N_{Rec,ave}$ in pulsatile flow in his study on heat transfer to liquids. Cotton (12) proposed an empirical equation for $N_{Rec,ave}$ for pulsatile flow in a tube. Hershey and Im (26) and Ury (81) used friction factor versus Reynolds number plots to obtain $N_{Rec,ave}$ for pulsatile flow in tubes and oscillating liquid columns, respectively. Ury (81) proposed an equation for $N_{Rec,ave}$ based on $N_{Re,ave}$ with the same average kinetic energy as a corresponding steady flow.

The most comprehensive works to date on experimentally determining $N_{Rec,ave}$ for incompressible, Newtonian, pulsating flow in a rigid, circular tube are by Gilbrech and Combs (22) and Sarpkaya (62). Gilbrech and Combs (22) used a double refraction technique and Sarpkaya (62) used pressure transducer measurements to obtain curves of $N_{Rec,ave}$ versus U_{amp} with α as a variable. Both measured the growth rate of turbulent slugs of fluid for $N_{Re,ave}$ up to 5000, α in the range of 4-16, and U_{amp} from 0-1. Although their results do not agree in absolute magnitude, the trends of their data are identical. They observed that for fixed U_{amp} , $N_{Rec,ave}$ decreases as α increases. Their data also show that for certain combinations of U_{amp} and α , pulsatile flow is more stable than corresponding steady flow. Yellin (85), from

his observations of growth rate and intermittancy in the same range of similarity parameters as Gilbrech and Combs and Sarpkaya, explains the second observation with the concept of a dimensionless relaxation time. This relaxation time is a measure of how long a pulsatile flow spends and how far it goes while below its $N_{Rec,ave}$ value. The longer the relaxation time, the more time there is for disturbances to be dissipated.

As previously stated, it is believed that the effect of frequency is more important than the effect of amplitude on the critical Reynolds number. Using Stokes' second problem (63) instead of a rigid tube analysis of the Navier-Stokes equations as a model for pulsatile flow, it can be crudely shown that $N_{Rec,u} = \frac{D U_{u,max}}{\nu}$ is directly proportional to α ($N_{Rec,u} = K\alpha$) (50). Nerem, Seed and Wood (50) verified this dependency in vivo in the ascending and descending aorta of dogs and obtained proportionality constants between $N_{Rec,u}$ and α . In the study of Nerem et al. (50), U_{amp} varied from 3-8. Clarion and Pelissier (9), in a study on the transition to turbulence in a free oscillatory flow, report that $N_{Rec,u}$ is proportional to α to the 0.8 power ($N_{Rec,u} = K\alpha^{0.8}$). Since the constant, K , is positive in both the studies of Nerem et al. (50) and Clarion and Pelissier (9), $N_{Rec,u}$ increases with increasing α . This is in opposition to the trend of decreasing $N_{Rec,ave}$ with increasing α as shown in the work of Gilbrech and Combs (22) and Sarpkaya (62).

If the critical Reynolds number ($N_{Rec,\delta}$) is based on Stokes layer thickness (δ) (boundary layer thickness from the solution of Stokes' problem) instead of pipe diameter, $N_{Rec,\delta}$ is a constant. This has been verified experimentally, and theoretical predictions of $N_{Rec,\delta}$

using stability theory give results of the same order of magnitude as the experiments. Davis (16) reviewed the application of stability theory to time periodic flows, and some further work on the subject with direct applications to arterial flow has been done by Danton, Jouvenel, and Oddou (13, 14). The experimental literature on $N_{Rec,\delta}$ has also been reviewed by Davis (16). Another review on oscillating boundary layer transition was presented by Loehrke, Morkovin, and Fejer (39).

Merkli and Thomann (44), Hino, Sawamoto, and Takasu (27), Clarion and Pelissier (9), and Sergeev (70) experimentally studied the transition to turbulence in oscillatory pipe flow. The first three investigators (9, 27, 44) used hot-film anemometry while Sergeev (70) used a strain gauge to make measurements. Sergeev (70) studied $N_{Re,u}$ from 4000-30000 and α from 4-40. The range of values of $N_{Re,u}$ and α studied by Merkli and Thomann (44) were not reported. However, the range of their experimental system was piston amplitudes of 2.85-13.8 mm and frequencies from 0-130/sec for air at 10^5 N/m² and 298°K in 19 mm diameter pipes. The similarity parameters studied by Hino et al. (27) and Clarion and Pelissier (9) are discussed later under pulsatile and oscillatory velocity profiles.

In the work of Hino et al. (27), two types of transition to turbulence were observed. The first type occurred at low $N_{Re,u}$ or $N_{Re,\delta}$ and high α when small scale disturbances were observed throughout the laminar velocity profile. As α was increased, transition was observed at lower $N_{Re,u}$. In other words, for this type of transition, higher frequency destabilized the flow. At higher $N_{Re,u}$, when α was above a critical value, another type of transition occurred. It was observed

that for rapid flow decelerations there was a spontaneous breakdown of laminar flow to turbulence and a resumption of laminar flow with acceleration. The return to laminar flow is called relaminarization. Turbulence during decelerated flow followed by relaminization has been observed by almost every experimental investigator studying the transition to turbulence in pulsatile or oscillatory flow, and is the type of flow studied in this investigation. Theoretically, the instability of decelerated flows has been demonstrated by Shen (72).

Hino et al. (27), Sergeev (70), and Merkli and Thomann (44) reported values of $N_{Rec,\delta}$ for transition. Their values are of the same order of magnitude as previous experiments and theoretical predictions for $N_{Re,\delta}$ which can be found in the review by Davis (16) and the articles by Hino et al. (27) and Merkli and Thomann (44). Nerem and Rumberger (47) recalculated their in vivo $N_{Rec,u}$ data (50) on the basis of $N_{Rec,\delta}$. It is interesting to note that the in vivo values of $N_{Rec,\delta}$ published by Nerem and Rumberger (47) are also in the range of all the other experiments.

Clarion and Pelissier (9) observed what they term low frequency and high frequency disturbances in oscillatory flow. They associated these disturbances with transition and turbulence, respectively. The disturbances were further characterized by regimes of the similarity parameters in which they appeared. This type of characterization of the flow is similar to the one proposed by Nerem and Seed (49) for arterial flow.

Velocity profiles for transitional oscillatory flow have been presented by Clarion and Pelissier (9) and Hino et al. (27). Clamen and

Minton (8) published velocity profiles for pulsatile transitional flow. Clarion and Pelissier (9) and Hino et al. (27) used hot-film anemometry while Clamen and Minton (8) used a hydrogen bubble technique. Clamen and Minton (8) used a very interesting setup to achieve a pulsatile flow. They oscillated the pipe harmonically instead of pumping the fluid. Hino et al. (27) investigated $N_{Re,u}$ from 105-5830 and α of 1.91-8.75. Clamen and Minton (8) studied $N_{Re,ave}$ between 1275-2900, α of 11.2-26.7, and U_{amp} from 0.5-5.4. Clarion and Pelissier (9) studied α of 1.43-16.12. It was not possible to calculate the range of $N_{Re,u}$ used by Clarion and Pelissier from the data given in their article, but they report another similarity parameter which is the ratio of the fluid displacement (X_{max}) to the pipe radius (R). Values of X_{max}/R from 2-50 were studied.

Clamen and Minton (8) also measured the intermittency of the flow in their experiments. Intermittency is the percentage of time a flow spends in the turbulent state. They found that intermittency for different U_{amp} at different $N_{Re,ave}$ correlated well when plotted against $N_{Re,u}$ (harmonic Reynolds number in their study).

Tromans and Peronneau, Sandman, and Xhaard have also experimentally studied flow stability in pulsatile flow. A short description of their work can be found in a review by Brocher (4). Other studies on transitional and turbulent pulsatile flow have been carried out by Thomas and Min (78) and Thomas and Shulka (79) who have applied surface renewal theory to the boundary layer problem.

Turbulent Pulsatile Flow Studies

Almost all of the past work on turbulent flow concentrated on the investigation of steady flow phenomena. However, the increasing number of practical applications of pulsatile flow has recently stimulated a growing interest in its study. The first experimental investigation of pulsating turbulent flow was done by Schultz-Grunow (66). He studied low frequency, large amplitude pulsations and found that quasi-steady behavior occurred. In other words, friction factors and other quantities for turbulent pulsatile flow can be predicted using instantaneous average velocity and steady flow friction factor data. Further work confirming the quasi-steady model for predicting pulsatile flow phenomena for low frequencies has been done by Streeter and Wylie (76) and Baird, Round, and Cardenas (2). A dissenting opinion on the usage of a quasi-steady model for low frequency pulsating flow has been published by Safwat and Polder (60).

In further investigations Brown, Margolis, and Shah (5), Lu, Nunge, Erian, and Mohajery (40), Kingston (33), and Ohmi, Usui, Tanaka, and Toyama (54, 55) have characterized pulsating turbulent pipe flow by establishing analytical models and investigating the similarity parameters under which their models apply. For small amplitude flows, Brown et al. (5) proposed a model with three frequency regimes. The model states that at low frequencies a quasi-steady model applies, at high frequencies a frozen eddy viscosity model (the eddy viscosity profile across the pipe does not have a chance to change since the velocity is oscillating back and forth so rapidly) is adequate, and in the intermediate regime the eddy viscosity profile changes in a complex way.

Brown et al. (5) found excellent agreement between their experiments and theory for the high frequency regime, but did not investigate the other regimes experimentally. They studied α between 31.6-774.6 and $N_{Re,ave}$ between 1100-100000. Measurements were made with pressure transducers.

Lu et al. (40) proposed a relationship of the similarity parameters for which the quasi-steady model applies based on their own experiments and those of others. The relationship is $0.025 \times N_{Re,ave} > \alpha^2$. Lu et al. (40) also observed that for small amplitudes compared to the average velocity, $N_{Re,ave}$ and α are the only parameters of importance. However, for larger amplitudes, U_{amp} is also important. Lu et al. (40) carried out experiments using hot-film anemometry over a wide range of the similarity parameters. They studied $N_{Re,ave}$ between 16000-81600, α between 0-64.3, and U_{amp} from 0-6.8.

Kingston (33) extended the work of Brown et al. (5) and Lu et al. (40) by further developing eddy viscosity models for the low and high frequency regimes and experimentally verifying their applicability. Hot-film anemometry was used to study the similarity parameter $\alpha^2/N_{Re,ave}$ in the range of 0.0095-0.24. This formulation is used to compare with the transition relation for quasi-steady turbulence proposed by Lu et al. (40). Kingston (33) also developed a one-dimensional periodic viscous sublayer model (boundary layer model) for turbulent pulsatile flow. This model also has three frequency regimes like the model of Brown et al. (5).

Ohmi and Usui (54) also developed an eddy viscosity model for a turbulent pulsating pipe flow. Ohmi et al. (55) obtained experimental data using hot-wire anemometry and pressure transducers. They studied

$N_{Re,ave}$ from 7740-95000 and α from 3.29-154. Ohmi and Usui (55) observed that the time averaged pulsatile flow velocity profiles agree well with comparable steady flow velocity profiles. This was also observed by Lu et al. (40) and is evidence for a quasi-steady model for pulsating turbulent flow in a pipe.

Gerrard (21) studied pulsatile turbulent flow in a pipe at one set of values of the similarity parameters. The values were $N_{Re,ave} = 3770$, $\alpha = 14.40$, and $U_{amp} = 0.573$. However, at only two points in the flow cycle, $\omega t = 0$ and $\omega t = \pi/2$, velocity profiles were measured. The experiment was performed by photographing dye sheets produced by electrolysis. Since a low value of $N_{Re,ave}$ was selected, the effects of relaminarization strongly affected the results.

Mizushima, Maruyama, Hirasawa, and Shiozaki (45, 46) studied pulsating turbulent flow in a pipe with pressure transducers and an electrochemical method. They measured instantaneous velocity in order to gain a better understanding of the structure of turbulence. Most of their work was done for $N_{Re,ave}$ of 10000 and α between 8.97-21.03. In one of their studies (46), an empirical relationship for a critical value of the period of pulsation (T_c) as a function of $N_{Re,u}$ was proposed in order to characterize their experimentally determined velocity and turbulence intensity profiles. The relationship is $T_c U_{ave}/D \approx 0.19 N_{Re,ave}^{2/3}$ for $2300 < N_{Re,ave} < 100000$, or in terms of frequency parameter, $\alpha_c^2 \approx 8.27 N_{Re,ave}^{1/3}$. Velocity and turbulence intensity profiles were divided into two types according to T_c . For values above T_c (low α), the velocity profiles resemble steady flow turbulent velocity profiles and the turbulence intensity profiles do not pulsate. For values

below T_c (high α), the velocity profiles do not resemble steady flow turbulent velocity profiles and the turbulence intensity pulsates. Mizushima et al. (45, 46) also studied bursting phenomena in turbulent pulsating pipe flow. Bursting phenomena are related to the events which occur in the coherent structures of turbulence. The concept of coherent structures in turbulence is briefly discussed in the next section.

Experimental velocity profiles for turbulent pulsatile flow in a pipe have been published by Schultz-Grunow (66), Lu et al. (40), Kingston (33), Gerrard (21), Ohmi et al. (55), and Mizushima et al. (45, 46). Friction factor correlations were presented by Baird et al. (2) and Safwat and Polder (60). Turbulence intensity data has been published by Lu et al. (40) and Mizushima et al. (45, 46). Mizushima et al. (46) also published shear stress, Reynolds stress, and eddy viscosity profiles for turbulent pulsatile pipe flow.

Another area of work in pulsatile turbulent flow is boundary layer flow. Karlsson (31) experimentally studied a pulsatile turbulent boundary layer at one Reynolds number with varying frequencies and amplitudes. He found that the effect of pulsation amplitude was negligible for the parameters studied. Patel (56) also experimentally studied a pulsatile turbulent boundary layer and reported that average pulsatile velocity profiles are identical to corresponding steady flow velocity profiles in the experimental range studied. The amplitude of the pulsations was small in both studies. Houdeville, Desopper, and Cousteix (29) published data on the average velocity and on the turbulence intensity for a pulsating turbulent boundary layer. Jonsson

took measurements of the velocity in a rough, oscillating, turbulent boundary layer. Jonsson's study is reviewed by Brocher (4). Patel (56) and Houdeville et al. (29) have proposed theories in an attempt to predict their experimental results.

Visual Studies Background

There has been very little work done on flow visualization for pulsatile transitional and turbulent flows. Gerrard (21) photographed dye sheets to obtain velocity profiles at one set of values of the similarity parameters for two points in the flow cycle. Merkli and Thomann (44) used flow visualization by smoke in an oscillating pipe flow. They found persistent vortices near the wall for laminar flow which disappeared with the onset of turbulence. From their observations, a value of $N_{Rec,\delta}$ was calculated. Clarion and Pelissier (9) studied a free oscillatory flow in a U-tube by a flow visualization technique. Vortices were also observed in their study for various values of the similarity parameters. Sergeev (70) reported a flow visualization with aluminum powder particles in a pipe, but did not specifically report any results of the oscillatory flow visualization experiments.

One school of thought on steady turbulent flow is that the phenomenon is totally random and should be treated by statistical methods alone. However, in recent years coherent structures in steady turbulent flow have been observed experimentally. This indicates that purely statistical methods are insufficient to totally solve the turbulence problem. Visual studies have played a large part in the discovery of coherent structures in steady turbulent flow.

Brodkey and his co-workers have accomplished much with visual studies. They determined a series of events occurring in steady turbulent flow. Through the coherent flow structures, they attempted to achieve a basic physical understanding of steady turbulent flow. The technique used was to suspend particles in a fluid to mark the fluid motions, and to take high speed motion pictures of the fluid from a convective viewpoint. Corino and Brodkey (10) investigated the wall region in turbulent flow in a tube. Nychas, Hershey, and Brodkey (52) studied turbulent flow along a flat plate. Praturi (57) studied turbulence along a flat plate using a three-dimensional photographic technique. The works of Corino and Brodkey (10), Nychas et al. (52), and Praturi (57) will be used to briefly describe the structure of turbulence which they found. For further references on visual studies in turbulent flow and the coherent structures of turbulence, Praturi's (57) dissertation should be consulted.

The basic sequence of events observed by Brodkey and his co-workers can be divided into four parts: deceleration, acceleration, ejection, and sweep. Deceleration occurs when a local low speed region of fluid is observed near the wall. A high speed region of fluid moves in behind the low speed fluid and begins to interact with it. This is the acceleration event. The ejection event occurs when small portions of the low speed fluid move away from the wall and violently interact with the high speed fluid. The high speed fluid then sweeps the events out of the field of view. These events occur randomly in space and time. This short discussion shows how visual studies can contribute to the understanding of turbulent flow. For a more detailed discussion of

the events, their relation to turbulence production, and further references, the works of Brodkey et al. (10, 52, 57) should be consulted.

THEORETICAL BASIS

A very important question about transitional and turbulent pulsatile flow is what similarity parameters are necessary to completely characterize the flow? Also, on what similarity parameters does the critical Reynolds number depend? In the literature section, work was presented which states that three similarity parameters, $N_{Re,ave}$, α , and U_{amp} , are sufficient to characterize pulsatile flow. For some cases (small amplitudes or oscillatory flow), only two parameters, $N_{Re,ave}$ or $N_{Re,u}$ and α , are necessary. In this section, a theoretical basis is presented for the three-similarity parameter theory for tube flow and the dependence of $N_{Re,ave}$ on α and U_{amp} . A simpler theory based on an oscillating flat plate leading to a two-similarity parameter dependence is also presented.

Rigid Tube Analysis

For incompressible, Newtonian flow in a rigid, smooth, cylindrical tube with zero velocity components in the radial and azimuthal directions, the equations of continuity and motion reduce to

$$\rho \frac{\partial U}{\partial t} = - \frac{\partial P}{\partial z} + \mu \left(\frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \frac{\partial U}{\partial r} \right) \quad (1)$$

where

$$\frac{\partial P}{\partial z} = \frac{\partial P}{\partial z}(t)$$

and

$$U = U(r,t)$$

(for example, see Uchida (80)). Equation (1) is general since it applies to all flows, laminar, transitional, or turbulent, as long as the assumptions are met. However, equation (1) can not be directly applied to turbulence since there are random fluctuations of the velocity in all three coordinate directions. A more exact equation would be the short time average of the equations of continuity and motion

$$\begin{aligned}
 \rho \frac{\partial \bar{U}}{\partial t} &= -\frac{\partial \bar{P}}{\partial z} + \mu \left(\frac{\partial^2 \bar{U}}{\partial r^2} + \frac{1}{r} \frac{\partial \bar{U}}{\partial r} \right) - \frac{\rho}{r} \frac{\partial}{\partial r} \overline{ru_r u_z} \\
 &\quad - \frac{\partial \bar{P}}{\partial r} - \frac{\rho}{r} \frac{\partial}{\partial r} \overline{ru_r^2} + \rho \frac{\overline{u_\theta^2}}{r} = 0 \\
 &\quad - \frac{1}{r} \frac{\partial \bar{P}}{\partial \theta} - \rho \frac{\partial}{\partial r} \overline{u_\theta u_r} - 2\rho \frac{\overline{u_\theta u_r}}{r} = 0
 \end{aligned} \tag{2}$$

where

$$U = \bar{U} + u_z \text{ and } P = \bar{P} + p.$$

The general equations for turbulent flow in cylindrical coordinates can be found in Hinze (28). The assumptions for equation (2) are incompressible, Newtonian flow with no average velocity in the radial or azimuthal directions, and velocity fluctuations which are functions of radial position only. The reason for short-time averaging is to average out the velocity fluctuations associated with turbulence while leaving the oscillating velocity component unaffected. Again, it should be pointed out that this averaging procedure, which was defined in the Introduction, only applies if the time scale of the turbulent fluctuations is much smaller than the time scale associated with the oscillatory component of the velocity.

For the analysis to be presented, equation (1) will be used instead of equation (2) since it is only the similarity parameter dependence of the flow which is of concern and not the exact magnitude of the velocity components. Any of the Reynolds stress terms $(\overline{uu})$ will give a Reynolds number dependence under dimensional analysis. Reynolds number dependence is already included in other terms of the differential equation. Equation (1) is exact for the determination of the similarity parameter dependence of the critical Reynolds number since the flow is laminar until transition.

The method used to derive the final differential equations for the flow is a generalization of the work of Uchida (80). For pulsatile flow, the flow can be thought of as an oscillatory motion superposed on a steady motion and the pressure gradient can be expressed as

$$\frac{\partial P}{\partial z}(t) = \frac{\partial P_s}{\partial z} + \frac{\partial P_u}{\partial z}(t) \quad (3)$$

where $\frac{\partial P_s}{\partial z}$ is a constant. The velocity can be expressed as

$$U(r,t) = U_s(r) + U_u(r,t). \quad (4)$$

Substituting equations (3) and (4) into equation (1), differential equations for U_s and U_u are generated. They are

$$-\frac{\partial P_s}{\partial z} + \mu \left(\frac{d^2 U_s}{dr^2} + \frac{1}{r} \frac{dU_s}{dr} \right) = 0 \quad (5)$$

and

$$\rho \frac{\partial U_u}{\partial t} = -\frac{\partial P_u}{\partial z} + \mu \left(\frac{\partial^2 U_u}{\partial r^2} + \frac{1}{r} \frac{\partial U_u}{\partial r} \right). \quad (6)$$

As previously stated, the solution of equations (5) and (6) is exact for the laminar flow problem in pulsatile flow, but cannot be used for an exact solution of the turbulence problem. For turbulence the short-time average equation of motion, equation (2), should be used and the short-time average pressure gradient and velocity, $\frac{\partial \bar{P}}{\partial z}$ and $\bar{U}$, should be represented by their steady and oscillatory components. However, it should be pointed out that in this case the equations generated for U_s and U_u will have no exact analytical solution since there are more unknowns than equations. This is a general problem with finding analytical solutions for turbulent flow.

A dimensional analysis is performed on equation (6) to show what the pertinent similarity parameters are for pulsatile flow. The dimensionless variables are chosen as

$$U' = U_u/U_{ave}, \quad z' = z/R, \quad r' = r/R, \quad P' = P_u/(\frac{1}{2} \rho U_{ave}^2), \quad \text{and} \quad t' = \omega t. \quad (7)$$

Equations (7) are substituted into equation (6) and the results rearranged to give a nondimensional equation of motion which is

$$\frac{R^2 \omega}{\nu} \frac{\partial U'}{\partial t'} = -\frac{1}{4} \frac{DU_{ave}^{\rho}}{\mu} \frac{\partial P'}{\partial z'} + \left(\frac{\partial^2 U'}{\partial r'^2} + \frac{1}{r'} \frac{\partial U'}{\partial r'} \right). \quad (8)$$

The groups in front of the pressure gradient and unsteady acceleration are the similarity parameters Reynolds number and frequency parameter defined as

$$N_{Re,ave} = DU_{ave}^{\rho}/\mu \quad (9)$$

and

$$\alpha = R\sqrt{\omega/\nu}. \quad (10)$$

The nondimensional equation of motion can then be rewritten as

$$\alpha^2 \frac{\partial U'}{\partial t'} = -\frac{1}{4} N_{Re,ave} \frac{\partial P'}{\partial z'} + \left(\frac{\partial^2 U'}{\partial r'^2} + \frac{1}{r'} \frac{\partial U'}{\partial r'} \right) . \quad (11)$$

This analysis shows that the dimensionless oscillatory velocity profile is a function of $N_{Re,ave}$ and α or

$$U' = U'(N_{Re,ave}, \alpha), \quad (12)$$

Therefore, the flow can be characterized by three similarity parameters:

$N_{Re,ave}$, α , and a third parameter representative of velocity amplitude.

Since for pulsatile flow, U' will vary throughout the flow cycle, another means will be chosen to represent velocity amplitude. An amplitude parameter is defined as

$$U_{amp} = U_{u,max}/U_{ave} \quad (13)$$

where $U_{u,max}$ is the maximum amplitude of the oscillatory portion of the velocity.

The next step is to determine the similarity parameter dependence of the critical Reynolds number for pulsatile flow. Gilbrech and Combs (22), from the analytical solution for pulsatile laminar flow, "assumed that the critical value of the Reynolds number should be determined by the shape of the laminar velocity profiles and, therefore by the parameters" of frequency and amplitude. Since equations (5) and (6) are exact up to the point of transition, the results of the dimensional analysis, equation (12) and the ensuing definition of U_{amp} , lead to the conclusion that

$$N_{Rec,ave} = N_{Rec,ave}(\alpha, U_{amp}). \quad (14)$$

It should be noted that the functional dependence of equation (14) also includes the effects of the steady motion because equation (5) is really a simplification of equation (6). The functional dependency of equation (14) has been verified experimentally by Gilbrech and Combs (22) and Sarpkaya (62).

Flat Plate Analysis

The literature on pulsatile flow for the transitional and turbulent states shows many instances where the effect of amplitude can be neglected. For simple oscillatory flow, a two-similarity parameter dependence of the flow can be shown. An analysis based on Stokes (boundary) layers on an oscillating flat plate will be presented next which will show that $N_{\text{Rec},u}$ is a linear function of α .

For laminar, incompressible, Newtonian flow along an infinite flat plate with unidirectional velocity, the equations of continuity and motion reduce to

$$\frac{\partial U}{\partial t} = \nu \frac{\partial^2 U}{\partial z^2} \quad (15)$$

where

$$U = U(z, t).$$

Equation (15) can be solved with the initial and boundary conditions

$$\begin{aligned} t \leq 0, \quad U &= 0 \quad \text{for all } z \\ t > 0, \quad z = 0, \quad U &= U_{u,\text{max}} \cos(\omega t) \end{aligned} \quad (16)$$

and

$$z = \infty, \quad U = 0$$

The solution is

$$U = U_{u,max} e^{-z\sqrt{\omega/2\nu}} \cos(\omega t - z\sqrt{\omega/2\nu}). \quad (17)$$

For the details of the solution of this problem, called Stokes second problem, refer to Schlichting (63). This problem is applicable to arterial flow because the harmonic boundary condition is a crude simulation of the pulse rate. Also if phenomena near the wall (in the boundary layer) are of interest, the curvature of a tube can be neglected and the problem can be thought of as flow along a flat plate.

A Stokes (boundary) layer thickness (δ) can be defined for a point in the cycle as the place where the instantaneous velocity equals a certain percentage of the maximum velocity or

$$U/U_{u,max} = K_1 = e^{-K_2} \cos(K_3 - K_2) \quad (18)$$

where

$$K_2 = \delta\sqrt{\omega/2\nu},$$

$$K_3 = \omega t,$$

and

$$0 < K_1 \leq 1 \quad (\text{usually } K_1 = 0.01).$$

Since t is a constant for a point in the cycle, equation (18) can be solved by trial and error for K_2 or the boundary layer thickness

$$\delta = K_2 \sqrt{2\nu/\omega}. \quad (19)$$

It has been shown both experimentally and theoretically that the critical Reynolds number based on Stokes layer thickness is a constant (see Literature Review for references) or

$$N_{\text{Rec},\delta} = \frac{\delta U_{u,\text{max}}}{\nu} = K_4. \quad (20)$$

Substituting equation (19) into equation (20) and using the definitions of $N_{\text{Rec},u}$ and α , the final result is

$$N_{\text{Rec},u} = \frac{DU_{u,\text{max}}}{\nu} = K\alpha. \quad (21)$$

Nerem et al. (50) proposed this analysis and verified equation (21) experimentally.

One other point about the flat plate analysis is that if a dimensional analysis is performed on equation (15) a two-similarity parameter dependence of the flow is demonstrated. The relationships are

$$U' = U'(\alpha) \quad (22)$$

and

$$N_{\text{Rec},u} = N_{\text{Rec},u}(\alpha). \quad (23)$$

EXPERIMENTAL PROGRAM

Purpose

The purpose of this study is to investigate the coherent flow structures of oscillatory flow during transition and turbulence. It has been shown that transition to turbulence may occur in blood flows in the large arteries of large animals and humans. This is the major physical motivation for this study. Therefore, values of the similarity parameters, $N_{Re,u}$ and α , in the normal human physiological range were studied.

The coherent flow structures of oscillatory transitional and turbulent flow are also of interest from a purely fluid mechanical point of view. The existence of coherent structures for steady turbulent flow is a well established fact. Comparison of the oscillatory flow structures with the steady flow structures is another goal of this study. It was also desired to study the variation of the oscillatory flow structures with $N_{Re,u}$ and α . The variation of the oscillatory flow structures with α is extremely important, since it is known that for both transitional and turbulent pulsatile flow, critical values of α exist where the flow changes from a quasi-steady to an oscillatory form.

Plan

In order to accomplish these goals, high speed motion pictures of oscillatory flow in the transitional and turbulent states were taken. A fluid marked with tracer particles was used to visualize the flow structures. The geometry used was a straight, rigid, glass pipe of constant cross section. Enough entry length was provided on either side of the section where the photography was performed to insure fully developed flow. A discussion of the meaning of fully developed flow for oscillatory flow is presented in Appendix A. A simple harmonic motion was used as the driving force for the flow. A convective viewpoint was achieved by moving the camera in phase with the flow driving force. However, it was possible to vary the distance the camera travelled, and therefore, match the flow velocity with the camera velocity at different radial positions near the wall. The similarity parameters, $N_{Re,u}$ and α , were independently varied over the range of interest.

Part of the equipment and procedures used in this study were developed by Corino (11), Carpenter (6), and others who previously worked on the flow system and photographic techniques. However, the flow system and photographic and lighting system were totally redesigned for an oscillatory flow study. A detailed description of the materials and equipment, experimental procedures, preliminary experiments, and calculations for this study are presented in the remainder of this chapter. A discussion of the design of the equipment used in the experiments is presented in Appendix A.

Materials and Equipment

Test Fluid. Trichloroethylene (TCE) was used as the test fluid. TCE was selected because its refractive index is almost equal to that of Pyrex glass pipe. This is a very important property for photographic work. TCE has a viscosity of 0.55 cp at 25°C and 0.446 cp at 50°C. Its density is 1.46 gm/ml at 25°C. Dow Chemical Company donated the NEU-TRI TCE.

Tracer Particles. Seemag grade magnesium oxide (MgO) particles manufactured by the FMC Corporation were used as the fluid tracers. The density of MgO is 3.59 gm/ml. Further information on MgO-TCE suspensions can be found in the Preliminary Experiments section and the work of Corino (11).

Particle Suspension Equipment. A Model 625 Precision Scientific oven was used to dry the MgO. The MgO was sieved with 42, 65, 100, 200, 250, and 325 mesh screens in a RO-TAP Testing Sieve Shaker. The screens had openings of 354, 210, 149, 74, 63, and 44 microns, respectively. Suspension of the MgO in TCE was accomplished with an Eppenbach colloid mill model number QV6-3B-6708-EXSP.

Pipe Unit. The pipe unit was originally built by Corino (11) and modified by others in the course of their work. For this study, it was completely revamped. A schematic diagram of the pipe unit and its accessories is shown in figure 3 and pictures and drawings are shown in figures 4, 5, 6, 7, and 8.

The section of the pipe unit where the photographic work was done is called the visual test section (figure 4). It was a 2.54 cm (1 in.) ID, 304.8 cm (10 ft) long Pyrex glass pipe surrounded by a

Figure 3. Schematic diagram of the pipe unit and its accessories.

Figure 4. View of the visual test section, camera, light source, and camera carriage.

FIGURE 4

Figure 5. View of the piston and cylinder, scotch yoke, flywheel, drive system, and gearing system.

FIGURE 5

Figura 6. Closeup view of the scotch yoke, flywheel, and drive system.

FIGURE 6

Figure 7. Side view drawing of the scotch yoke and flywheel to illustrate its principle of operation.

Figure 8: Closeup view of part of the gearing system.

FIGURE 8

trough with a glass window through which the light source shines. During the experiments, the trough was filled with TCE to provide a medium with a continuous index of refraction. The trough was vented to the building ventilation system and the ventilation was below the trough because TCE vapors are denser than air. For some experiments, a ruler stretched across the glass pipe just on the edge of the field of the camera was photographed as a check on the camera velocity.

Flanged to each end of the visual test section were entry sections (figures 4 and 5) provided to insure fully developed flow. The entry sections were 2.54 cm (1 in.) ID hydraulically smooth pipe. The rear (attached to glass stand pipe) and front (attached to input-output lines) entry sections were 701.0 cm (23 ft) and 609.6 cm (20 ft) long, respectively. The rear entry section was flanged to a 5.08 cm (2 in.) ID, 182.9 cm (6 ft) long Pyrex glass stand pipe which was vented. Thermowells with thermometers were located on the far ends (away from the visual test section) of each entry section so that the temperature of the TCE could be measured for viscosity calculations. The front entry section had openings (originally drilled for pressure taps) used for bleeding out air bubbles.

The rest of the pipe unit consisted of the input-output lines and the piping leading to the piston and cylinder. This piping was galvanized, Schedule 40 with 1.27 cm (1/2 in.), 2.54 cm (1 in.), and 5.08 cm (2 in.) nominal diameter pipe in the lines. A small pump manufactured by the Viking Pump Company was used to transfer TCE into and out of the pipe unit. There was a 5 micron Flotronics microfilter in the input line to remove dirt from the TCE. The pipe unit, including

the piston and cylinder, had a capacity of approximately 0.0189 m^3 (5 gal) of TCE.

Piston and Cylinder. The piston and cylinder (figure 5) was a converted Rivett hydraulic device. The front of the cylinder was machined to fit a 5.08 cm (2 in.) nominal diameter, Schedule 40 pipe. The piston and gasket seals were replaced with teflon seals since TCE dissolves most rubbers and plastics. A 5.08 cm (2 in.) nominal diameter, Schedule 40, galvanized stand pipe was connected to the cylinder to prevent overflow of TCE. The stand pipe was 236.22 cm (7-3/4 ft) long and was vented. The cylinder was 11.43 cm (4-1/2 in.) I.D. and the apparatus had a maximum stroke length of 22.86 cm (9 in.).

Scotch Yoke and Flywheel (figures 5, 6, and 7). The scotch yoke was a rectangular piece of cold rolled steel with a $1.91 \times 2.54 \times 20.32$ cm ($3/4 \times 1 \times 8$ in.) slot machined in the center. One side was connected to the piston and cylinder and the other side had a rack welded on. In the slot a 1.91 cm ($3/4$ in.) O.D., 1.27 cm ($1/2$ in.) I.D., 2.54 cm (1 in.) long brass bearing slid up and down. The brass bearing was connected to a flywheel by a 1.27 cm ($1/2$ in.) pin. The pin could be connected to the flywheel at radial distances from the flywheel center of 2.54 cm (1 in.), 3.81 cm ($1-1/2$ in.), and 5.08 cm (2 in.). The flywheel was 27.94 cm (11 in.) in diameter and 1.91 cm ($3/4$ in.) thick. The scotch yoke was spring loaded. The purpose of this apparatus was to translate a circular motion from the flywheel into a linear harmonic motion in the scotch yoke (see figure 7).

The flywheel was notched at each quarter cycle at the points of maximum and minimum velocity and as the flywheel rotated it tripped

two micro switches mounted on the flywheel four times a cycle. One switch was connected to the event marker of a recorder and was used to obtain the period of a cycle. The other switch was wired to the timing light of the camera and was used to calculate the framing speed of the film.

Drive System (figures 5 and 6). The scotch yoke and flywheel were driven by a Graham Variable Speed Transmission model number 150 VM with a 0 to 450 revolution per minute (rpm) output. The transmission drove an Ohio Gear Uniline 262 speed reducer with a 20 to 1 reduction and the flywheel was mounted on the output shaft of the speed reducer. This gave the drive system an output of 0 to 22.5 rpm. The transmission and speed reducer were connected by chain and sprocket.

Gearing System. The purpose of the gearing system (figures 5, and 8) was to provide an input to the camera carriage which would move the camera in phase with the flow driving force, while also allowing the camera velocity to be matched to the fluid velocity at different radial distances from, but near, the pipe wall. The first requirement was accomplished by attaching the gearing system directly to the scotch yoke, and the second one by designing the gearing ratios properly and including a variable gear in the system. The gearing system was comprised of these parts: 20 pitch, 20° pressure angle rack sliding in a machined slot and 40 tooth, 5.08 cm (2 in.) pitch diameter spur gear to match, 80, 72, and two 15 tooth sprockets, number 50 roller chain, Floyd Variable Speed reducer model number S1A56H2, and a Plessey, Inc. Angle Gear with a 1 to 1 reduction ratio. The rack was driven by the

scotch yoke and drove the spur gear. Therefore, the displacement of the scotch yoke determined how far the spur gear revolved. The sprockets were set up to increase the revolutions of the spur gear by $80/15$ ($5-1/3$) multiplied by $72/15$ ($4-4/5$) times, producing a total gearing ratio of 25.6. This was the input to the Floyd Variable Speed Reducer which had a 0 to 1 output to input ratio in forward or reverse. The output of the Floyd Variable Speed Reducer went to the Plessey Angle Gear which changed the direction of motion by 90° . The Plessey Angle Gear was connected to the drive shaft of the camera carriage.

Camera Carriage. The camera carriage (figures 4 and 5) was an old Industrial Nucleonics Source Detector converted for the purposes of this study. It had an output to input ratio of 12.38 cm/turn (4.875 in./turn) of the drive shaft and a maximum travel distance of 165.1 cm (65 in.). The instantaneous camera displacement was monitored by a 10 turn Helipot potentiometer made by Beckman Instruments, Inc. geared to the drive shaft. The potentiometer was connected to a Bausch and Lomb VOM 6 recorder. Rulers mounted on the camera carriage were also used to measure the camera displacement. The carriage ran on brass on steel bearings and was driven by chain and sprockets. The camera was attached by heavy steel supports.

Photographic and Lighting Equipment. The camera (figure 4) was an Eastman High-Speed Camera Type III. The camera was driven by a Bodine motor with a Minarik controller. It had a framing speed of approximately 20 to 300 frames per second (fps) and a timing light to measure the framing speed. The lens used was a Kodak Anastigmat $f/2.7$, 63 mm focal length. For closeup work which was necessary for this study, a 6.25 cm (2.5 in.) extension tube was attached between the lens and

the camera. The extension tube also increased the magnification of the lens making it easier to follow the particles. An LW Photo-Optical Data Analyzer model 224-A was the projector used to study the films. It could slow down the projection speed to 1 fps, project at 24 fps, and also project at intermediate speeds. The lens on the projector was a 2 in. focal length, $f/1.6$, Ektanar lens made by Kodak. The film used was 16 mm Kodak TRI-X Reversal Film 7278 with an ASA 160 in tungsten light. The film came in 30.5 m (100 ft) rolls and there were 4000 frames per roll. Processing was done through the Department of Photography and Cinema at The Ohio State University and Bennett Motion Picture Labs of Columbus, Ohio.

The light source (figure 4) was three D.V.Y., 120 volt, 650 watt, quartzline lamps arranged in a triangular configuration. A piece of highly reflective metal was mounted behind the lamps. In front of the lamps there was an adjustable slit used to produce a narrow beam of light. A double convex lens of 33 mm diameter and 65 mm focal length was placed between the lamps and the slit. The purpose of the lens was to concentrate the light from the lamps into a narrower beam. Air was blown over the lamps to cool them. This light source arrangement was the product of much trial and error.

The conditions for proper exposure of the film were achieved through test motion pictures and experiments made with a model trough and pipe. The model trough and pipe was built to simulate the visual test section. Light intensity was measured with a Luna Pro exposure meter. The specific conditions pertaining to the photographic and lighting parameters are discussed in the Preliminary Experiments section.

Experimental Procedures

The details of the experimental procedures are discussed in this section. The discussion is a general one and does not delve into the specific values of most of the variables. Details, including the values of the similarity parameters and the photographic, lighting, and particle parameters, can be found in the Experimental Conditions and the Preliminary Experiments sections.

Preparation of the MgO-TCE Suspension. The procedure for preparing the MgO-TCE suspension used in this study is similar to the method of Carpenter (6). Some of the steps outlined were not used in the preparation of the suspensions for the test motion pictures. Only steps 1 and 3 to 6 were used for the test motion pictures. However, the total procedure gave the highest yield of <44 micron particles before suspension. The procedure is as follows:

1. Dry the MgO in the oven in 55 mm aluminum pans at 100 to 110°C for 24 hours.
2. Ball mill the MgO.
3. Sieve the MgO in the sieve shaker using a 325 mesh screen.
4. Repeat steps 2 and 3 and wash the screen periodically to unclog the pores. When the yield of particles becomes small start again with step 1 and fresh MgO.
5. Save the <325 mesh (<44 micron) particles. For the test motion pictures, other size screens were used and other size particles were collected.
6. Disperse the MgO in TCE in the colloid mill. A 5 gal volume of TCE was always used. In this study, a gap setting of 4 and a 60 sec recirculation were used. Other gap settings and recirculation times were tried when preparing the suspension for the test motion pictures, but varying these parameters did not appear to affect the properties of the suspension. Remove the MgO-TCE suspension from the colloid mill with the mill on.

7. Allow the particles to settle. Measure the maximum settling height and calculate the settling time required for the specified particle size according to Stokes law. Siphon the MgO-TCE suspension leaving the settled particles.
8. Repeat steps 6 and 7 after allowing the suspension to settle for a few hours. Continue until the proper particle concentration is reached according to the exposure meter reading. Dilute the suspension to 5 gal as necessary.
9. Mix different particle size suspensions as necessary to obtain better photographic properties of the suspension.

Preparation of the Pipe Unit. The procedure is as follows:

1. Drain the pipe unit as thoroughly as possible.
2. Swab the inside of the visual test section and the entry sections until clean and reassemble the pipe unit.

Operating Procedure. This procedure is used whenever motion pictures are taken. The procedure is as follows:

1. Prepare the MgO-TCE suspension and pipe unit as previously described and focus the camera as described below.
2. Grease the camera carriage and scotch yoke. Oil the rack, slot, and chains. Check the oil levels on the variable speed drive, speed reducer, and variable speed reducer and add oil as necessary. Clean the glass pipe and glass window of the trough with window cleaner. Clean the trough.
3. Remove the stand pipe caps. Turn on the air to the light source. Turn on the recorder and camera controller to warm up. Plug in the timing light.
4. Set the flywheel radius.
5. Shake the prepared MgO-TCE suspension and allow it to settle for the required time.
6. At the required settling time, pump the MgO-TCE suspension into the pipe unit through the input lines with the transfer pump bypassing the filter. Turn on the variable speed drive when TCE starts coming into the visual test section

and keep the suspension moving to avoid settling. Stop the transfer pump when the TCE is about 2/3 of the way up the rear stand pipe. Add more MgO-TCE suspension as necessary during the experiment.

7. Fill the trough with filtered TCE so that the glass pipe is totally covered.
8. Bleed out any air bubbles from the pipe unit with the tap on the front entry section.
9. Check the focusing, slit size, and slit position.
10. Turn on the light source, take an exposure meter reading, and turn off the light source.
11. Load the film into the camera and set the framing speed on the camera controller to obtain at least one 1/2 cycle per roll of film.
12. Set the variable speed reducer to the highest speed at which the system will operate and set the variable speed drive for the correct $N_{Re,u}$ and α by timing the event marker for one cycle.
13. Check for particle settling. If it occurs speed up the variable speed drive and reset for the correct rpm.
14. Turn on the light source and take the motion pictures. Start the camera at a known time in the flow cycle by using the event marker. Have the recorder on before and after the camera is started.
15. Turn off the light source and measure the maximum camera displacement from readings of the rulers when the camera is at rest at opposite ends on the camera carriage.
16. Turn the variable speed reducer to 0, remove the film from the camera, and read the thermometers on the ends of the entry sections.
17. Repeat steps 10 to 16 for other motion pictures.
18. Pump the MgO-TCE suspension back into its container through the output line with the transfer pump. Turn off the variable speed drive. Drain the TCE from the trough back into its container through filter paper. Turn off the recorder, camera controller, air to the light source, and cap the stand pipes.

Measurement of the Depth of Field of the Lens System. The pro-

cedure is as follows:

1. Set a piece of graph paper at a measured angle from the camera.
2. Set the f/stop and focusing ring of the lens.
3. Focus the camera on a marked line on the graph paper by moving the graph paper.
4. Measure the distance on the graph paper which is in focus.
5. Calculate the depth of field of the lens system from the measured angle, the distance in focus, and a trigonometric relationship for a right triangle between the two.

Focusing the Camera on the Same Plane as the Light Source. The

procedure is as follows:

1. Set the slit size, f/stop, and focusing ring.
2. Set a piece of graph paper on a slip stick so that it is on the diameter of the pipe in the model trough and pipe. Fill the model trough and pipe with TCE.
3. Turn the graph paper parallel to the lens and focus on a marked line by moving the model trough and pipe.
4. Turn the graph paper parallel to the light source and turn on the air and light source. Adjust the light beam so that it is split in two by a line on the graph paper which is in the middle of the pipe.
5. Lock the light beam into position, redo steps 3 and 4, and make minor adjustments.
6. Measure the perpendicular distance between the front of the lens and the middle of the slit.
7. Measure the outer diameter of the glass pipe.
8. Calculate the distance from the top of the glass pipe to the front of the lens so that the light beam from the slit will be parallel to the plane of the diameter of the glass pipe.

9. Set the camera on the camera carriage supports according to step 8 and framed so that the inside pipe wall is at the edge of the frame.

Determining Proper Exposure, Particle Properties, and Framing

Speed. The procedure is as follows:

1. Focus the camera, prepare test MgO-TCE suspensions, and prepare the pipe unit as previously described. Record the following:
  - a. f/stop
  - b. focusing
  - c. slit size
  - d. particle concentration
  - e. particle size
2. Take test motion pictures following the operating procedure. Record the following:
  - a. particle settling time
  - b. framing speed
  - c. exposure meter reading
3. If any motion picture is properly exposed at any framing speed, proceed to the next step. If not, the light reaching the film must be adjusted and more test motion pictures taken.
4. From the proper exposure at one framing speed, extrapolate the proper exposure for other framing speeds. This is done through the exposure meter reading. The calculation is presented in the Preliminary Experiments section.
5. Calibrate the model trough and pipe by taking an exposure meter reading using the same slit size and particle properties as when used on the camera carriage.
6. Change the light source arrangement and slit size until proper exposure according to step 4 is achieved on the model trough and pipe.
7. Determine the particle size from settling requirements. Use the model trough and pipe to test the suspension for proper exposure meter reading. In this way, following steps 6 to 9 in the preparation of the MgO-TCE suspension, determine the correct particle concentration and particle settling time.
8. Repeat steps 1 and 2 to determine framing speed.

Preliminary Experiments

The necessary conditions to properly photograph the flow were determined by experiment before the final motion pictures were taken. There were three criteria which had to be achieved. First, enough light to properly expose the film at framing speeds fast enough to slow down the particle motions for viewing was needed. Secondly, a two-dimensional view was necessary. Thirdly, particle suspensions of size and concentration sufficient to reflect enough light to the camera for proper film exposure while following the fluid motions had to be provided. The experimental conditions to satisfy the above criteria were determined from principles of photography, calculations, model experiments, observations on the visual test section, and trial and error test motion pictures. The photographic, lighting, and particle parameters are discussed in this section. Tables 7 and 8 in the Experimental Conditions section list the actual values used.

Photographic Parameters. The most important photographic parameter to ensure a two-dimensional view was the depth of field of the lens system. Depth of field is defined as the distance in front of and behind an object which is in sharp focus. The smaller the depth of field, the more two-dimensional is the view.

The factors which affect depth of field are lens aperture (f /stop), focal length, object distance, viewing magnification, and viewing distance. Viewing magnification and viewing distance were not considered. The focal length of the lens was 63 mm. The largest lens aperture of $f/2.7$ was chosen because it provided the smallest depth of field and also allowed the most light to reach the film. The object

distance was chosen as the point of focus with the lens racked all the way in (called ∞). The ∞ setting was chosen because it was easily reproducible.

With the lens set at $f/2.7$ and ∞ , the depth of field was measured as outlined in the Experimental Procedures section. The graph paper was set at a 60° angle from the front of the camera lens and a section of approximately 5 mm long was observed to be in focus. The depth of field of the lens system was approximately 4.3 mm ($5 \sin 60^\circ$). This was about 17% of the diameter of the pipe. It should be mentioned that the depth of field was not measured in a TCE system. This will have a slight effect when extrapolated to the visual test section.

Another important photographic parameter was the total magnification at which the motion pictures were viewed on the screen. With a knowledge of the total magnification, it was possible to plot particles on a piece of graph paper and then to calculate back to the actual dimensions of the visual test section. The total magnification was calculated from the measurement of the distance between two $1/16$ in. marks of a photographed ruler with the distance of the film plane of the projector to the screen set at 127 cm (50 in.). The measured length of $1-3/8$ in. compared with the actual length of $1/16$ in. gives a total magnification of 22X. All measurements on the screen were made at this magnification.

The volume of the field of view was determined by the depth of field of the lens system and the length and width the camera saw. The depth of field was 4.3 mm and the length and width of the field of view were measured as 9.5 mm and 7.3 mm. Only about 8.2 mm of the length

of the field of view was in the flow. The field of view of the camera is shown in figure 9 along with the orientation of the field of view to the polar coordinate axes. Figure 9a is a cut in the $r\theta$ plane and figure 9b is a cut in the rz plane along the θ position which bisects the depth of field. Although the camera viewed a volume of fluid, three-dimensional effects were not discernable by this photographic technique. The observed field of view on the screen was the plane shown in figure 9b. The effect of depth of field on the field of view was that tracer particles moved in and out of focus.

The final photographic parameter of importance was focusing the camera. Focusing was done as described in the Experimental Procedures section. At first, focusing was done in air and the camera was then transferred to the visual test section. Since it was necessary to focus near the pipe wall, focusing in air was unsatisfactory because Pyrex glass and TCE, though very close in index of refraction, are not exactly equal. The light rays were bent slightly out of focus as they went through the glass. This problem was solved by focusing on the model trough and pipe with TCE in both.

Lighting Parameters. The factors affecting lighting for this study were light intensity, light source distance to the object, slit size, lens aperture (f /stop), framing speed, extension tube length, film speed, and particle concentration. The lens aperture was determined from depth of field considerations, but $f/2.7$ was the largest aperture of the lens and the most advantageous for lighting. The extension tube length was 62.5 mm. The film speed for TRI-X Reversal Film 7278 in tungsten light was ASA 160. The other parameters were

Figure 9. Field of view of the camera. (a) Along the pipe, $r\theta$ plane. (b) Above the pipe, rz plane. (All dimensions are in mm.)

still to be determined. The problem was to get enough light to the film for proper exposure.

An exposure meter and the model trough and pipe were used as an aid in determining the conditions for proper exposure of the film, but calculations based on exposure meter readings only gave a ballpark estimate. Two reasons the exposure meter readings may have been off were the use of an extension tube and the insensitivity of film speeds at low and high framing speeds (reciprocity effect). Trial and error test motion pictures were used to determine the final conditions. Light intensity, light source distance to the object, slit size, framing speed, and particle concentration were varied to achieve an optimum combination. The procedures used are described in the Experimental Procedures section.

The slit size was an important parameter for not only did it affect exposure, but it also affected depth of field. The larger the slit was, the more field of view there was exposed because of a wider beam of light. The objective was to have a light beam narrower than the depth of field of the lens system. However, the more the light beam was narrowed, the less light there was for exposure of the film. Light source distance to the object also affected the size of the light beam, but advantageously. The closer the light source was to the object, the narrower the light beam and the more intense the light. Therefore, the light source was placed as close to the object as possible. Different slit sizes and arrangements were tried until a design with a concentrating lens was decided upon. The slit size was set by placing a 2.7 mm thick strip of metal in the slit and closing the slit down on

the metal. The light beam size was measured on the visual test section with TCE in the trough and pipe. The point of measurement was on the pipe diameter nearest and perpendicular to the light source. The light beam size was 2-3 mm at the most concentrated portion of the light beam. This was between 8 to 12% of the pipe diameter and 46 to 70% of the depth of field.

Light intensity, framing speed, and particle concentration were still variables. Framing speed was limited by the speed necessary to slow down the particles for viewing. However, the faster the framing speed, the less light the camera shutter let in, and the more intense the light source needed to be for proper exposure of the film. The convective viewpoint of the camera made it possible to use slower framing speeds than otherwise possible. Particle concentration had a small effect on the light level (see tables 1 and 2). However, at high particle concentrations, the suspension became cloudy, scattered the light, and did not allow enough light to reach the film. At low particle concentrations, the light passed straight through the suspension and was not reflected from the particles to the film. Therefore, with an estimate of the proper framing speed and particle concentration, light intensity was varied until approximate proper exposure was achieved. Framing speed and particle concentration were then varied to fine tune the exposure.

Test motion pictures were taken along with exposure meter readings at various framing speeds. For all exposure meter readings, it was attempted to place the exposure meter in the same position (at 45° from the lens facing the light source, and sometimes at 45° from the lens

Table 1
Exposure Meter Readings for Calculating Exposure

Amount of MgO (gm)	Exposure Meter Readings ^a	
	Particle Size ^b (microns)	
	<44	44-61
5 ^c	12	13 1/3
10 ^c	14	14
10 ^d	14 1/3	14

- a. Light source: 1 DVY bulb, slit narrow.
- b. The suspension was shaken and allowed to settle 7 1/2 minutes. The particle size reported here is from the sieve trays used to make them.
- c. These readings were taken on the visual test section. The film was properly exposed at 20 fps.
- d. Calibration of the model trough and pipe.

Table 2

Exposure Meter Readings on the Model Trough and Pipe

Settling Time ^a (min)	Exposure Meter Readings			
	Particle Size ^b (microns)			
	<44 ^c	44-61 ^c	<44 ^d	44-61 ^e
2 1/2	<15 1/3	15-15 1/3	<15 2/3	-
5	15	15	>15 1/3	-
7 1/2	>14 2/3	<14 2/3	15 1/3	16 1/2 / 17 1/2
10	14 2/3	14 1/3	<15 1/3	-

- a. The suspension was shaken and 250 ml samples were siphoned off at these times.
- b. Each suspension had 10 gm of MgO and the particle size reported is from the sieve trays used to make them.
- c. Light source: 3 DVY bulbs in a row, slit narrow.
- d. Light source: 3 DVY bulbs in a triangular configuration, slit narrow.
- e. Light source: 3 DVY bulbs in a triangular configuration, slit widened to 2.7 mm, and a converging lens inserted between the light and the slit.

perpendicular to the light source. Exposure meter readings for motion pictures which were properly exposed at 20 fps are presented in table 1.

From the exposure meter readings in table 1 and the exposure meter scales relating f/stop and shutter speed, the light intensity necessary for higher framing speeds was estimated. For ASA 160, f/2.7, and an exposure meter reading of 14, the exposure meter gave a shutter speed of about 1/125 sec. The shutter for the camera allowed light to expose the film 1/5 of the time. Therefore, the calculated framing speed was $125 \text{ fps} \times 1/5 = 25 \text{ fps}$. This calculation agreed with the actual exposures at 20 fps. From previous test motion pictures with the slit wide open, exposure was possible up to 160 fps. From visual observations of the films, framing speeds this high were necessary to slow down the particle motions. Using 150 fps, a shutter speed of $1/150 \text{ sec} \times 1/5 = 1/750 \text{ sec}$ was necessary. This necessitated an exposure meter reading of at least 16-2/3.

At this point, the model trough and pipe came into use. First, the model trough and pipe were calibrated for exposure meter reading. This was done by using the same conditions of particles and light as were used in the properly exposed motion pictures at 20 fps. The model trough and pipe calibration exposure meter readings are presented in table 1 and the calibration was considered one to one. The light intensity was modified by changing the light source and checking on the model trough and pipe until an exposure meter reading of at least 16-2/3 was achieved. The details are presented in table 2.

Final framing speed was now determined with more test motion pictures. Framing speeds between 125 and 200 fps were used. Henceforth, all runs on the visual test section were checked for an exposure meter

reading of 16-2/3 or more. The effect of particle concentration on the light level is discussed under particle parameters.

Particle Parameters. Two physical properties of the MgO-TCE suspension, particle concentration and particle size, were varied to produce a suspension with adequate photographic properties. The major effect of particle size was on the manner the particles followed the fluid motions. Particle concentration affected particle-particle interactions and also had an effect on the amount of light reflected from the particles to the film. The effect of particle size on lighting, at least for the particle sizes studied, is shown in tables 1 and 2. When everything else is equivalent, changing the particle size from 44-61 microns to <44 microns had little effect on the light level.

Particle concentration was controlled by the amount of MgO in the suspension and the settling time allowed before the suspension was pumped into the pipe unit. Particle size was also controlled by settling time and the mesh size used to produce a certain size range of particles. The smallest mesh size available produced particles 44 microns or less. Particle ranges <44 microns were produced by settling the MgO particles in TCE and siphoning. Settling times (t) were calculated from the terminal settling velocity (U_t) of a spherical particle under the influence of gravity, bouyancy, and Stokes drag. Table 3 presents settling times for various particle diameters (d) of MgO in TCE. A settling height (x) of 38.1 cm (15 in.) was used in the calculations because it was the height of the TCE in its storage container.

Originally a <10 micron particle suspension was chosen. However, the <10 micron suspension was not photographically adequate under the

Table 3
Particle Settling Times of MgO in TCE at 25°C

d (microns)	d (cm)	Mesh Size ^a	U_t^b (cm/sec)	t^c (min)	$N_{Re,t}^d$
0.5	5.00×10^{-5}		5.27×10^{-5}	1.20×10^4	7.0×10^{-7}
1.0	1.00×10^{-4}		2.11×10^{-4}	3.01×10^3	5.6×10^{-6}
5.0	5.00×10^{-4}		5.27×10^{-3}	1.20×10^2	7.0×10^{-4}
10.0	1.00×10^{-3}		2.11×10^{-2}	30.12	5.6×10^{-3}
20.0	2.00×10^{-3}		8.43×10^{-2}	7.53	4.5×10^{-2}
44.0	4.40×10^{-3}	325	0.41	1.56	0.48
50.0	5.00×10^{-3}		0.53	1.20	0.70
61.0	6.10×10^{-3}	250	0.79	0.81	1.27
74.0	7.40×10^{-3}	200	1.16	0.55	2.28
100.0	1.00×10^{-2}		2.11	0.30	5.60
149.0	1.49×10^{-2}	100	4.68	0.14	18.50

a. Tyler Standard Sieve Series.

b. Calculated from $U_t = d^2(\rho_{MgO} - \rho_{TCE})g/18\mu_{TCE}$.

c. Calculated from $t = x/U_t$ where x is the maximum settling height possible.

d. Defined as $d U_t \rho_{TCE}/\mu_{TCE}$. The equation in footnote (b) is only rigorously applicable if $N_{Re,t} < 0.5$.

conditions of photography and lighting already established and discussed in the previous section. On the other hand, the <44 micron suspension was adequate photographically. Therefore, a combination of <44 micron and <10 micron suspensions was the final choice. Details of the preparation of MgO-TCE suspensions and the tests to determine the correct particle concentration and size are presented in the Experimental Procedures section. Supplementary material on the final choice of the particle parameters of the MgO-TCE suspension and some calculations which indicate that the suspension adequately followed the fluid motions are presented in the remainder of this section.

From observations on the visual test section with <44 micron and 44-61 micron particles, no particle settling was observed for $N_{Re,u} > 20,000$. However, during runs at $N_{Re,u}$ of about 14,000 and 6500, particle settling was observed. Not only did this show that all the particles were not following the fluid motions, but it also drastically reduced the light level. Smaller particles therefore had to be used. The reason smaller particles were not originally used was that suspensions of smaller particles required siphoning and reconcentrating until sufficient particle concentration was present for proper film exposure and this method was quite time consuming. Sieves were available down to 44 microns, so most test motion pictures were shot with <44 micron or greater particle size with no siphoning and reconcentrating.

With particle size specified (<10 microns was the original choice), the correct particle concentration had to be achieved for proper exposure of the film. The correct particle concentration was known from the previously determined exposure meter reading of 16-2/3 or

better. The suspension was prepared and then tested for exposure meter reading in the model trough and pipe. If the exposure meter reading was not sufficient more MgO was added in the colloid mill and the procedure was repeated. Table 4 gives the details. Overall, 360 gm of <44 micron MgO were used. The settling temperature of the suspension was always a few degrees below 25°C. This means particles a little larger than 10 microns were present. It is possible that even larger particle sizes were present in the suspension since the MgO particles tend to agglomerate.

The <10 micron suspension was shown to be photographically inadequate by further test motion pictures. A compromise was made between particle size and photography. A mixture of 2000 ml of <10 micron suspension described in table 4 with <44 micron suspension containing 10 gm of MgO to make 18.9 l (5 gal) was used when taking the final motion pictures. A settling time of 7½ min was used before pumping the suspension into the pipe unit. Therefore, only <20 micron particles were pumped into the pipe unit according to table 3. The suspension was always kept in motion while in the pipe unit to avoid settling.

After the suspension was prepared and shaken, it appeared cloudy in its container (1 ft diameter), but clear in the visual test section (1 in. diameter). Particles could be seen in the container with a strong flashlight and easily in the visual test section with the light source on. Some settling was noticed in the container after 30 min, and after a day or two most of the particles had settled out. Very small particles could be seen in suspension after a day or two. Some

Table 4

Exposure Meter Reading Versus Amount of MgO for <10 Micron Particles

Amount of MgO ^a (gm)	Settling Time ^b (min)	Exposure Meter Reading
10 ^c	7 1/2	17 1/2
60	0	15
	2 1/2	15
	5	15
92	0	15
120	0	15 2/3
150	0	16
181	0	16 1/3
208	0	16 2/3
238	0	17
270	0	17 2/3
270 ^d	3	16 2/3
300	3	17
330	3	16 1/3
360	3	17
360 ^e	3	17 1/3
360 ^f	1	17 1/2 / 17 1/2
	3	16 2/3 / 17 1/3

- a. The total amount of MgO added. MgO is added in the colloid mill and settled according to Stokes law so that <10 micron particles remain in suspension.
- b. The container with the MgO-TCE suspension is shaken and a sample is taken at this time.
- c. This is a reference for which the motion pictures are properly exposed in the test films. It is with <44 micron particles. This and all other readings for this table are on the model trough and pipe.
- d. The suspension is diluted by adding about 4000 ml (1 gal) of TCE.
- e. The suspension is diluted by adding about 2000 ml (1/2 gal) of TCE.
- f. The suspension is diluted by adding about 1500 ml (3/8 gal) of TCE. This suspension was mixed with a suspension of <44 micron particles and was the suspension used for the final motion pictures.

settling was noticed in the visual test section during low $N_{Re,u}$ runs.

Calculations are presented to justify the choice of particle size and concentration of the MgO-TCE suspension. However, the final choice was based solely on the visual observations of the suspension in the visual test section and the results of the test motion pictures. A more complex analysis on whether the particles follow the fluid motions which includes turbulence was presented by Corino (11). Corino (11) also addressed the question of whether dilute MgO-TCE suspensions are Newtonian, and experimentally showed they are.

A simple model based on Stokes law was proposed by Corino (11) to account for the particles following the fluid motions. If a particle is accelerated by a fluid, the particle and fluid may have different accelerations. Applying Newton's second law of motion to a spherical particle under acceleration in the axial direction in a pipe and assuming that Stokes drag is the only retarding force acting on the particle, the following relationship can be developed

$$3\pi \mu_{TCE} d(U_{TCE} - U_{MgO}) = \frac{4}{3} \pi \frac{d^3}{8} \rho_{MgO} \frac{dU_{MgO}}{dt} \quad (1)$$

Rearranging,

$$U_{TCE} = U_{MgO} + \frac{d^2 \rho_{MgO}}{18\mu_{TCE}} \frac{dU_{MgO}}{dt} \quad (2)$$

If $d^2 \rho_{MgO}/18\mu_{TCE}$ is small then the particles should follow the fluid for moderate accelerations. For 44 micron particles, the largest size used and the worst case, $d^2 \rho_{MgO}/18\mu_{TCE} = 2.86 \times 10^{-4}$ sec. The fluid

acceleration, dU_{TCE}/dt , can be estimated from $N_{Re,u}$ and α . For the worst case, $U_{u,max} = 32$ cm/sec and $T = 10$ sec. An estimate of the acceleration is $dU_{TCE}/dt = dU_{MgO}/dt = 32/10/2 = 6.5$ cm/sec². This makes $d^2\rho_{MgO}/18\mu_{TCE} dU_{MgO}/dt = 1.86 \times 10^{-3}$ cm/sec which is small when compared with the velocities in the pipe. However, Stokes drag was not the only force acting as a check of the Reynolds number shows ($N_{Re,t} = 12.6-37.4$ depending on $N_{Re,u}$), and these calculations can only be treated as crude estimates.

Particle-particle interactions were also treated in a simple manner following the treatment of Corino (11). The volume of fluid in view was $8.2 \times 7.3 \times 4.3$ mm³ (see figure 9). From particle counts on a frame, no more than 1000 particles were observed in a single frame. A spherical particle of 44 microns in diameter has a volume of 4.46×10^{-5} mm³. Therefore, the particles occupied no more than $1.73 \times 10^{-2}\%$ of the volume of the field of view. The particles were also evenly distributed throughout the field of view. This dilute concentration assured very little particle-particle interaction. Furthermore, the visual observation of particle collisions was rare in the films except on the wall where the particles tended to adhere.

Calculations

Period of a Cycle. The period of a cycle was calculated from a measurement of the rpm of the flywheel. The rpm was set by timing the event marker of the recorder for one cycle. The event marker was set off every quarter of a cycle by a micro switch on the flywheel. The period of a cycle is

$$T = 60/\text{rpm}. \quad (1)$$

Framing Speed. The framing speed was calculated from the period of a cycle and another micro switch on the flywheel which was connected to the timing light of the camera. Since only half a cycle was photographed per run, the framing speed is

$$\text{fps} = (\text{frames}/1/2 \text{ cycle})/T/2. \quad (2)$$

Viscosity. In order to calculate $N_{\text{Re},u}$ and α , it was necessary to know the viscosity of the fluid. Viscosity of a liquid at low pressures is a strong function of temperature and a weak function of pressure. Therefore pressure variations were ignored. From empirical evidence, the viscosity of a liquid varies with temperature exponentially as

$$\mu = C_1 e^{C_2/RT^*} \quad (3)$$

where C_1 and C_2 are constants, R is the ideal gas constant, and T^* is temperature. For TCE,

$$\mu = 0.55 \text{ cp at } T^* = 25^\circ\text{C}$$

and

$$\mu = 0.46 \text{ cp at } T^* = 50^\circ\text{C}$$

(International Critical Tables, Vol. III, p. 213). Equation (3) becomes

$$\mu = 0.037 e^{806.991/T^*} \quad (4)$$

where μ (=) cp and T^* (=) $^\circ\text{K}$. In the experiment, the temperature was measured by two thermometers, one at the far end of each entry section.

Both thermometers read the same temperature for all the runs. It was assumed that the density of TCE is not a function of temperature (a good assumption for a liquid) so that the temperature variation of the kinematic viscosity is the same as that of the viscosity for TCE.

Frequency Parameter. The definition of the frequency parameter is

$$\alpha = R\sqrt{\omega/\nu} \quad (5)$$

where

$$\omega = 2\pi/T$$

and

$$\nu = \mu/\rho.$$

Reynolds Number. The definition of the Reynolds number is

$$N_{Re,u} = D U_{u,max}/\nu. \quad (6)$$

$U_{u,max}$ was calculated from the relationship

$$U_{u,max} = \pi X_{max}/T \quad (7)$$

(see equations (2), (7), (8), and (9), Appendix A for the derivation).

X_{max} is directly related to the piston stroke length or scotch yoke displacement by

$$D^2 X_{max} = D_c^2 X_{pis} \quad (8)$$

(see equations (12), (13), and (14), Appendix A for the derivation).

X_{pis} was measured directly.

Camera Velocity. The camera velocity was calculated from a measurement of its displacement during half a cycle and the assumption that the camera velocity is a simple harmonic motion or

$$U_{cam} = U_{cam,max} \sin(2\pi t/T) \quad (9)$$

where

$$U_{cam,max} = \pi L_{cam}/T.$$

Camera Matching Position. The radial position from the wall where the camera velocity matches the fluid velocity can be estimated from the empirical steady flow relations for the velocity profile in turbulent flow (see equations (16) and (17), Appendix A) and the assumption that at every radial position the velocity is a simple harmonic motion with time (equation (4), Appendix A). The calculation was done by first estimating the friction velocity, U^* , from $N_{Re,u}$. At the matching velocity position, $U_{cam,max} = U_{u,max1}$. From this information and equation (16) in Appendix A, U^+ , y^+ , and y can be estimated.

EXPERIMENTAL RESULTS

Two similarity parameters, $N_{Re,u}$ and α , were chosen to characterize the purely oscillatory flow. This is sufficient as shown in the literature and the short theoretical discussion previously presented.

On the equipment, there were two variables, X_{pis} and rpm of the flywheel, which could be varied to control $N_{Re,u}$ and α . Over the range of parameters studied, it was desired to observe the effect of holding $N_{Re,u}$ constant while varying α and vice versa. Table 5 presents the experimental runs chosen to accomplish this.

Experimental Conditions

Since the geometry of the system was set, the only other variable which affected $N_{Re,u}$ and α was temperature through its strong effect on the viscosity of TCE. No temperature control was used on the equipment, but the experiment was run only if the temperature was near 25°C. For purely oscillatory flow the forward and reverse halves of the flow cycle are identical. Therefore, only one half of the cycle need be photographed. The same half cycle was photographed in every experiment and the framing speed was set so that at least one half cycle was photographed per roll for any set of conditions. The experimental conditions are presented in table 6 according to the grouping of $N_{Re,u}$ and α in table 5. The framing speed listed in table 6 is from a calibration curve for the camera. The calculated framing speeds are

Table 5
Proposed Experimental Runs^a

	x_{pis}^b (cm)	rpm ^b	$N_{Re,u}$	α
I. $N_{Re,u}$ constant, α variable				
A.	10.16	1	7263	6.70
	7.62	1 1/3	7263	7.73
	5.08	2	7263	9.47
B.	10.16	1 1/2	10895	8.20
	7.62	2	10895	9.47
	5.08	3	10895	11.60
C.	10.16	3	21790	11.60
	7.62	4	21790	13.39
	5.08	6	21790	16.40
II. α constant, $N_{Re,u}$ variable				
A.	5.08	2	7263	9.47
	7.62	2	10895	9.47
	10.16	2	14527	9.47
B.	5.08	3	10895	11.60
	7.62	3	16343	11.60
	10.16	3	21790	11.60

a. The physical properties of TCE are for 25°C.

b. There are a total of 11 experimental runs.

x_{pis} (cm)	rpm
10.16	1, 1 1/2, 2, 3
7.62	1 1/3, 2, 3, 4
5.05	2, 3, 6

Table 6
Experimental Conditions

Run ^a	$N_{Re,u}$ ^b	α^b	T^*c (°C)	fps ^d	1/2 cycles ^e	matching position y^+	y (cm)
IA. $N_{Re,u} \approx 7200$							
41	7068	6.61	23	150	1	4.05	.027
63	7198	6.67	25	125	1	5.94	.039
46	7329	7.77	27	150	1	6.29	.041
47	7329	7.77	27	150	1	6.44	.042
68	7231	7.71	25.5	150	1	6.43	.042
69	7231	7.71	25.5	150	1	6.43	.042
51	7428	9.58	28.5	200	1	13.48	.086
52	7428	9.58	28.5	200	1	12.10	.077
55	7198	9.43	25	200	1	19.19	.126
IB. $N_{Re,u} \approx 11000$							
40	10602	8.09	23	150	1	6.36	.030
60	10797	8.16	25	150	1	8.56	.039
61	10797	8.16	25	150	1	8.40	.039
44	10944	9.51	27	200	1	8.64	.039
45	10944	9.51	27	200	1	9.09	.041
66	10846	9.45	25.5	200	1	8.62	.039
67	10846	9.45	25.5	200	1	9.07	.041
49	11142	11.73	28.5	200	2	19.53	.087
50	11142	11.73	28.5	200	2	19.53	.087
54	10797	11.55	25	200	2	17.26	.079

Table 6 (cont.)

Run ^a	$N_{Re,u}$ ^b	α ^b	T^* ^c (°C)	fps ^d	1/2 cycles ^e	matching position y^+	position y (cm)
IC. $N_{Re,u} \approx 22000$							
37	21399	11.49	24	200	2	17.15	.043
38	21399	11.49	24	150	3	16.62	.042
56	21595	11.55	25	200	2	16.49	.041
57	21595	11.55	25	200	2	15.50	.039
42	21988	13.45	27	200	2	19.03	.047
64	21693	13.36	25.5	200	2	20.31	.050
48	22286	16.59	28.5	200	4	29.76	.072
53	21595	16.33	25	200	3	22.97	.057
IIA. $\alpha \approx 9.50$							
51	7428	9.58	28.5	200	1	13.48	.086
52	7428	9.58	28.5	200	1	12.10	.077
55	7198	9.43	25	200	1	19.19	.126
44	10944	9.51	27	200	1	8.64	.039
45	10994	9.51	27	200	1	9.09	.041
66	10846	9.45	25.5	200	1	8.62	.039
67	10846	9.45	25.5	200	1	9.07	.041
39	14266	9.38	24	150	2	9.12	.033
58	14396	9.43	25	200	1	9.41	.034
59	14396	9.43	25	200	1	9.60	.034

Table 6 (cont.)

Run ^a	$N_{Re,u}$ ^b	α ^b	T^* ^c (°C)	fps ^d	1/2 cycles ^e	matching position y^+	y (cm)
IIB. $\alpha \approx 11.60$							
49	11142	11.73	28.5	200	2	19.53	.087
50	11142	11.73	28.5	200	2	19.53	.087
54	10797	11.55	25	200	2	17.26	.079
43	16491	11.65	27	200	2	17.53	.056
65	16270	11.57	25.5	200	2	15.91	.050
37	21399	11.49	24	200	2	17.15	.043
38	21399	11.49	24	150	2	16.62	.042
56	21595	11.55	25	200	2	16.49	.041
57	21595	11.55	25	200	2	15.50	.039

- a. Each run is one roll of film.
- b. The corresponding values of X_{pis} and rpm for each set of $N_{Re,u}$ and α can be found in table 5.
- c. The viscosity of TCE is calculated at T^* using the correlation in the Calculations section. The density of TCE is assumed constant over the temperature range studied and the value for 25°C is used.
- d. This is the framing speed from a calibration curve for the camera. The actual framing speed is calculated from the event marker and the timing light and is presented in table 7.
- e. This is the number of half cycles photographed per roll of film which were amenable to analysis.

tabulated in table 7. The photographic, lighting, and particle parameters common to all experimental runs are listed in table 8.

Preliminary Analysis

From visual observations of the films, the flow cycle was divided into two states called quasi-laminar and quasi-turbulent. The quasi-laminar state was characterized by the tracer particles exhibiting motions parallel to the pipe axis with no noticeable component of radial motion. In the quasi-turbulent state, radial motions both toward and away from the pipe wall, large in comparison to the quasi-laminar state, were easily observable. The large radial motions of the quasi-turbulent state are one indication of turbulence.

The times in the flow cycle when the quasi-laminar and quasi-turbulent states occurred were established by use of the timing light on the film. The quasi-laminar state occurred as the flow accelerated from zero velocity up to a point in the cycle around the timing light signifying the middle of a half cycle. Just prior to or following the timing light signifying the middle of a half cycle, the flow exhibited the radial motions of the quasi-turbulent state. The quasi-turbulent state continued with repeated random bursts of large radial motions of the tracer particles until close to the end of the half cycle where the flow reversed direction, relaminarized, and the whole process reoccurred. There was also some dead time in the flow cycle at the beginning and end of each half cycle when the velocity of the particles was zero. The occurrence of transition with deceleration in a periodic flow is in agreement with previous results published in the literature.

Table 7
Calculated Framing Speeds

Run	rpm	T (sec)	f/1/2 cycle ^a	fps
37	3	20	----- 1944	----- 194.4
38	3	20	1599 1557	155.9 155.7
39	2	30	2077 -----	138.5 -----
40	1 1/2	40	3022	151.5
41	1	60	-----	-----
42	4	15	1435 1422	191.3 189.6
43	3	20	1854 1847	185.4 184.7
44	2	30	-----	-----
45	2	30	2809	186.5
46	1 1/3	45	-----	-----
47	1 1/3	45	3312	147.2
48	6	10	943 936 938 908	188.6 187.2 187.6 181.6
49	3	20	----- 1899	----- 189.9
50	3	20	1887 1886	188.7 188.6
51	2	30	2777	185.1
52	2	30	2780	185.3
53	6	10	928 935 936	185.6 187.0 187.2

Table 7 (cont.)

Run	rpm	T (sec)	f/1/2 cycle ^a	fps
54	3	20	----- 1856	----- 185.6
55	2	30	2795	186.3
56	3	20	1905 -----	190.5 -----
57	3	20	1952 -----	195.2 -----
58	2	30	2845	189.7
59	2	30	2841	189.4
60	1 1/2	40	2947	147.4
61	1 1/2	40	2986	149.3
63	1	60	-----	-----
64	4	15	1418 1416	189.1 188.8
65	3	20	1908 -----	190.8 -----
66	2	30	2786	185.7
67	2	30	2879	191.9
68	1 1/3	45	3504	155.7
69	1 1/3	45	3384	150.4

a. Frames per half cycle. The spaces with blanks have missing timing lights on the film.

Table 8

Photographic, Lighting, and Particle Parameters^a

f/stop of the lens	2.7			
focusing	∞			
particle size	<44 micron <10 micron			
particle amount ^b	<44 micron <10 micron	10 gm ?	about 18.9 l about 2.0 l	suspension suspension
settling time ^c	7 1/2 min			

- a. These parameters apply to all the experimental runs.
- b. The <10 micron particles were added to the <44 micron particle suspension by shaking an approximately 18.9 l sample of the <10 micron particle suspension and immediately siphoning off about 2.0 l.
- c. The MgO-TCE suspension was shaken and allowed to settle before pumping it into the pipe unit.

The purpose of the Preliminary Analysis section is to show which portions of the flow cycle were amenable to analysis for the experiments which were performed. It is also used to demonstrate that quasi-turbulent phenomena were not caused by equipment malfunctions, but were manifestations of the flow itself. A further result of this section is to quantify the data of one run to indicate that it is turbulence which was observed with the flow structures.

The motion of the camera alone is treated first. From visual observations and chart recorder output of the camera displacement (figure 10), it was evident that the camera motion was not a simple harmonic motion as originally planned. The positions of zero velocity were stretched out (dead time, point 4) and the camera jerked as it started in motion (point 5) and sometimes as it stopped. The severity of the problem varied with X_{pis} , rpm, and the output to input ratio of the variable speed drive (R_{oi}), increasing with increasing X_{pis} and R_{oi} and decreasing with increasing rpm. The extended portions of zero velocity and jerking of the camera were further verified by plotting camera travel distance (L_{cam}) versus frame for twenty frame intervals from films of the ruler stretched across the visual test section (figure 11). This was done for several values of X_{pis} , rpm, and R_{oi} . Camera velocity (U_{cam}) was calculated from the difference between two L_{cam} positions divided by the difference in frames and is also plotted in figure 11. Plotting versus frame is the same as plotting versus time since frame divided by framing speed (a constant for any film) is time. Points 1 and 2 in figure 11 illustrate the dead time and jerk. It was also noted from visual observations that the flow pulsed at the same time that the

Figure 10. Chart recorder output of the camera displacement for run 56.

Figure 11. Camera displacement and velocity for run 56 from photographing a ruler.

camera began its motion and sometimes when the camera stopped. From this analysis, it was decided not to attempt any analysis of the films in the region where the camera was starting or stopping its motion because any observed effects of the flow alone (transition, turbulence, or even laminar flow) would be confused with the superposition of camera disturbances and flow disturbances caused by the equipment. The region where the camera was stationary was also discarded for two reasons. It was feared that the effects of the equipment malfunction may have affected these regions and more importantly because it was believed that effects which pertain to transition and turbulence do not occur at these points in the cycle because of the low velocity of the flow.

The next problem to be discussed is the significance of the camera motion with respect to the particle motion in the quasi-laminar region. For these purposes a detailed quantitative analysis of one film was performed. This analysis is assumed representative of all the runs. Run 56, whose displacement and velocity are shown in figure 11, was chosen. For this analysis, particle displacements ($X_{z,ap}$ and X_r) were plotted frame by frame on a screen and camera displacements (L_{cam}) were also recorded. Velocity of the camera (U_{cam}), axial particle velocity ($U_{z,ap}$), and radial particle velocity (U_r) were calculated according to the definitions in table 9. Root mean square (rms) values of all the velocities (u'_{cam} , u'_z , and u'_r) and a correlation coefficient (R_{camz}) between U_{cam} and $U_{z,ap}$ were also calculated as defined in table 9. Plots of R_{camz} and the rms velocities versus frame for run 56 are presented in figures 12, 13, 14, and 15.

Table 9

Definitions of RMS Velocities and Correlation Coefficient

A. Velocities

$$U_{cam} = L_{cam2} - L_{cam1} / \Delta(\text{frame})$$

$$U_{z,ap} = X_{z,ap2} - X_{z,ap1} / \Delta(\text{frame})$$

$$U_r = X_{r2} - X_{r1} / \Delta(\text{frame})$$

$$\Delta(\text{frame}) = 1$$

B. Averaging

$$\bar{} = \Sigma / n$$

n = number of points used to average

C. Deviations

$$u_{cam} = U_{cam} - \bar{U}_{cam}$$

$$u_z = U_{z,ap} - \bar{U}_{z,ap} \quad (\text{ap is dropped})$$

$$u_r = U_r - \bar{U}_r$$

D. RMS Velocities

$$u'_{cam} = \sqrt{u_{cam}^2}$$

$$u'_z = \sqrt{u_z^2} \quad (\text{ap is dropped})$$

$$u'_r = \sqrt{u_r^2}$$

E. Correlation Coefficient

$$R_{camz} = \overline{u_{cam} u_z} / u'_{cam} u'_z \quad (\text{ap is dropped})$$

F. Notation

L_{cam} camera displacement

X_r, X_z particle displacement in the radial and axial directions

G. Subscripts

cam camera

r radial direction

z axial direction

z,ap axial direction, apparent velocity or position
(in general, z = z,ap + cam)

1, 2 positions of measurement of L_{cam} , X_r , and $X_{z,ap}$

Figure 12. Camera velocity and apparent axial velocity correlation coefficient for run 56.

Figure 13. Camera rms velocity for run 56.

Figure 14. Apparent axial rms velocity for run 56.

Figure 15. Radial rms velocity for run 56.

The procedure used to make the calculations of R_{camz} and the rms velocities is subject to criticism. However, no better procedure could be devised to obtain particle displacements and velocities from the motion pictures. The first criticism is that the particles follow three-dimensional paths, but only two dimensions are observed in the motion pictures. The second criticism is that different particles were plotted over different size intervals of frames, or that different time scales were used to short-time average each particle. The length of the lines in figures 12, 14, and 15 is the number of frames in the interval used for short-time averaging. The camera velocity (figure 13) was averaged over 20 frame intervals. The third criticism is that single particles sometimes appeared like dumbbells due to their speed, but the position of the particle was always taken as the center of the dumbbell.

The correlation coefficient, R_{camz} , between U_{cam} and $U_{z,ap}$ has some interesting properties. Since both U_{cam} and $U_{z,ap}$ were similar functions of time (the camera was mechanically linked to the piston), if the flow is laminar and the camera runs smoothly, then $R_{camz} = 1$ (see figure 16c). If there are any disturbances in the flow while the camera runs smoothly, whether caused by turbulence or malfunction of the equipment, then $R_{camz} < 1$ with a limit of 0 if the disturbances in the flow are totally random (see figure 16a and c). If the camera does not run smoothly, the situation is different because any change in the camera motion also affects the flow due to the Lagrangian or moving coordinate viewpoint of the camera. In actuality, $U_z = U_{z,ap} + U_{cam}$, where the apparent axial particle velocity on the right hand side is what was used to calculate u'_z and R_{camz} , and U_z on the left hand side

$$U_z = U_{z,ap} + U_{cam}$$

Figure 16. Meaning of R_{camz} . (a) and (b) Actual versus observed viewpoint. (Only laminar flow is represented. Turbulence would cause random disturbances in $U_{z,ap}$ and U_z .) (c) Limiting cases of R_{camz} .

is the actual axial velocity of a particle which would be observed by a stationary observer. The velocity of the moving coordinate system is U_{cam} . What this means is that for any jerk in the camera, the viewer observes an equal but opposite jerk in the flow on the screen (see figure 16b). This is a possible explanation for the jerks in the flow as the camera starts and stops its motion. In terms of R_{camz} , any unsmoothness in the camera causes $R_{camz} < 1$, but total randomness in U_{cam} causes $R_{camz} = -1$ for laminar flow (see figure 16c). Disturbances in the flow again will cause R_{camz} to approach zero for an unsmooth camera (see figure 16c).

In figure 12, there are many negative values of R_{camz} . Strongly negative values between -0.4 and -0.7 occur between frames 640 and 740 and again between frames 820 and 860. This means that the camera, flow, or both had a large amount of noise (unsmoothness) in them at these points. After the initial jerk in the flow, the flow appeared to run smoothly on visual observation. Since there were no values of $R_{camz} = 1$ or -1 , it is logical to conclude that there were some disturbances in the axial velocity (the flow is not totally laminar) and the rest of the contribution to R_{camz} was from the camera. It is believed that these flow disturbances were due to turbulence and not equipment malfunction because there was no apparent jerkiness in the flow on visual observation, though no absolute proof is given. This is why the region is called quasi-laminar. Turbulence throughout run 56 was not unexpected because of the high value of $N_{Re,u} = 21595$. The contributions to R_{camz} by axial turbulence and camera jerk cannot be separated by this analysis and effects of turbulence which may have occurred in the quasi-

laminar region were not investigated since they were not readily observable visually. The only visual evidence of axial turbulence in the quasi-laminar region was tracer particles which sped up and slowed down in relation to the camera while exhibiting axial motion only.

Finally, some quantitative results on the quasi-turbulent region are presented through the calculations of rms velocities for run 56. Quasi is used in this case because no other evidence besides visual observation and rms velocities are presented to support the case for turbulent flow. However, it is strongly believed that this region is turbulent for many of the values of $N_{Re,u}$ and α studied. Run 56 is among the turbulent cases and this was one reason run 56 was chosen for this analysis.

The rms camera velocity, u'_{cam} , is a measure of the noise in the camera. The axial and radial rms velocities, u'_z and u'_r , are measures of flow disturbances due to the equipment and/or turbulence. Flow disturbances due to the equipment of at least the same order of magnitude as the flow disturbances due to the observed radial motions (turbulence) were ruled out because the flow by visual observation of the fluid appeared to be smooth throughout the quasi-turbulent region. Furthermore, comparison of u'_{cam} with the jumps in u'_z and u'_r (done below) support the conclusion that the flow structures were not caused by the equipment. Two other points about the rms velocities are presented. Due to the definitions of u'_{cam} and u'_z as presented in table 9, both have a built-in time dependence. Therefore, u'_r is a better indicator of turbulence than u'_z . In steady turbulent flow, u'_z and u'_r are strong functions of radial position, especially near the

wall. This has also been shown to be true for periodic flow by Mizushima et al. (45, 46).

The noise level in the camera may be compared with the noise level in the apparent axial particle rms velocity for run 56, both in the quasi-laminar and quasi-turbulent regions. The plot of u'_{cam} versus frame for run 56, figure 13, shows that directly after the camera started in motion (frames 500-700; in the quasi-laminar region) there was a high level of noise in the camera. By the time the flow cycle reached the quasi-turbulent region (frame 900) the noise level in the camera calmed down to a fairly steady level. The average background noise level in the camera for run 56 was $u'_{cam} \approx 1.52$ cm/sec. Figure 14 shows that in the quasi-laminar region (frames 500-900) the average axial rms velocity of the particles was $u'_z \approx 0.95$ cm/sec, and in the quasi-turbulent region (after frame 900) peaks as high as $u'_z \approx 3.68$ cm/sec were observed. These numbers show that the events occurring in the quasi-turbulent region were manifestations of the flow and not caused by the equipment. As stated previously, the camera and the flow were observed to be running smoothly in the quasi-turbulent region and the peak noise level in the flow, u'_z , indicative of turbulence, was over two times the fairly constant average noise level of the camera, u'_{cam} , indicative of equipment noise.

The radial particle rms velocity, u'_r shown in figure 15, which is an even better indicator of turbulence activity than u'_z , jumped from an average $u'_r \approx 0.19$ cm/sec in the quasi-laminar region to peaks of $u'_r \approx 2.66$ cm/sec in the quasi-turbulent region. A comparison of the peak rms velocities with the peak centerline velocity, $U_{u,max} = 32$ cm/sec,

shows that $u_z'/U_{u,max} \approx 0.12$ and $u_r'/U_{u,max} \approx 0.08$. Comparison of the nondimensional rms velocities with values in the literature for steady turbulent flow show that they are of the same magnitude. This comparison gives greater confidence that it was really turbulence which was observed in the quasi-turbulent region.

Before proceeding to the discussion of the coherent flow structures, the results of the Preliminary Analysis section may be summarized as follows. The flow cycle was divided into two states, quasi-laminar and quasi-turbulent, according to the magnitude of the radial motion of the tracer particles. The camera motion was analyzed and was shown not to be a simple harmonic motion as originally planned. From visual observations, the same conclusion was made for the flow. It was decided not to investigate the regions of dead time in the flow cycle or the portions of the flow cycle where the camera was starting or stopping its motion. An analysis of the correlation coefficient between the camera and apparent axial particle velocity led to the conclusion that there was probably turbulence in the quasi-laminar region, although no absolute proof was given. However, the quasi-laminar region was not amenable to visual analysis because the effects of turbulence were not readily observable visually. In the quasi-turbulent region, comparison of the camera and apparent axial particle rms velocities showed that the effects of turbulence were manifestations of the flow and not the equipment. The large jump of the radial particle rms velocity between the quasi-laminar and quasi-turbulent regions indicated that turbulence was observed. The nondimensional axial and radial rms velocities also indicate a turbulent flow. These calculations are only for

$N_{Re,u} = 21595$ and $\alpha = 11.55$. In conclusion, only the quasi-turbulent region was amenable to analysis by this visual technique, and only the flow structures in the quasi-turbulent region are discussed in the remainder of the text.

The Structures of the Flow

The field of view of the camera was shown in figure 9 in the Preliminary Experiments section and is reproduced here again. It would help the reader to refer to this figure while reading the descriptions of the flow structures. Figure 9 contains the actual dimensions of the field of view of the camera and the orientation of the field of view to the polar coordinate axes.

Table 10 contains a calculation of the size of the field of view of the camera measured from the wall (rz plane) versus $N_{Re,u}$ in dimensionless coordinates. It should be noted that the calculation of dimensionless coordinates for oscillatory flow presented here is subject to criticism. The relationship $U_{ave} \approx 0.8 U_{u,max}$ is for steady turbulent flow. For oscillatory flow, $U_{ave} = 0$. However, the relationship between U_{ave} and $U_{u,max}$ was used as an estimate of the shape of the velocity profile for oscillatory turbulent pipe flow at a point in time ($U_{ave} = \frac{1}{A} \int_A U(r,t) |_{t_c} dA$). The other problem is that oscillatory flow varies with time and therefore so does the size of the dimensionless coordinates ($y^+ = yU^*/\nu$, $U^* = U^*(U_{ave})$). Therefore, all calculations of y^+ were based on the calculated maximum centerline velocity (a fixed time in the flow cycle), $U_{u,max}$, and the relationship $U_{ave} \approx 0.8 U_{u,max}$ is assumed to hold true.

Figure 9. Field of view of the camera. (a) Along the pipe, $r\theta$ plane. (b) Above the pipe, rz plane. (All dimensions are in mm.)

Table 10

Size of the Field of View of the Camera Versus $N_{Re,u}$
in Dimensionless Coordinates

$N_{Re,u}$	U^{*a} (cm/sec)	$y^{+a,b}$
7200	.58	126
11000	.83	181
14300	1.05	229
16300	1.18	253
22000	1.53	333

- a. The calculation of U^* and y^+ are described by equations (16) and (17) in Appendix A. The kinematic viscosity of TCE at 25°C is used in the calculation.
- b. The measured distance from the wall of the field of view of the camera is $y = 0.82$ cm as shown in figure 9.

In this description the flow field is divided into two parts, a wall region and an outer region. The distinction was made from visual observations of the film. The wall region was the region of the flow where most of the excited radial and rotational motions of the tracer particles were observed. The outer region was any portion of the flow field outside the wall region and was characterized by mainly rectilinear motions of the tracer particles. Table 11 presents the size of the wall region measured from the wall (rz plane) in both actual (y) and dimensionless (y^+) coordinates for values of $N_{Re,u}$ and α . The values of $N_{Re,u}$ and α in table 11 are averages of all the experimental data as presented in table 6 and the kinetic viscosity of TCE used in any further calculations is for 25°C. This form of presentation is used throughout the remainder of the text when discussing the general trends of the data.

A very brief description of the fluid motions in the quasi-turbulent state was presented in the introductory paragraph of the Preliminary Analysis section. The most striking effect was the large radial motions towards and away from the pipe wall. The large radial motions always occurred near or subsequent to the beginning of decelerated flow as marked by the timing light on the film. A more detailed description of the fluid motions in the quasi-turbulent region is presented here.

The coherent flow structures of oscillatory transitional and turbulent flow presented here are similar to the flow structures of steady turbulent flow as presented by Corino and Brodkey (10), Corino (11), and Nychas, Hershey, and Brodkey (52). Detailed comparisons are

Table 11

Observed Size of the Wall Region Versus $N_{Re,u}$ and α

$N_{Re,u}$	α	y^a (cm)	U^{*b} (cm/sec)	y^{+b}
7200	9.50	--	.58	--
7200	7.75	.24	.58	37
7200	6.65	.21	.58	32
11000	11.60	--	.83	--
11000	9.50	.21	.83	47
11000	8.10	.29	.83	64
14300	9.50	.22	1.05	63
16300	11.60	--	1.18	--
22000	16.40	.24	1.53	97
22000	13.40	.26	1.53	107
22000	11.60	.40	1.53	161

- a. The observed size is from the average over all the films at the $N_{Re,u}$ and α specified. The conditions which are blank exhibited no flow structures.
- b. The calculation of U^* and y^+ are described by equations (16) and (17) in Appendix A. The kinematic viscosity of TCE at 25°C is used in the calculation.

made in the Comparison of Results section, but two general comparisons are made now. Like the steady turbulent flow structures, the oscillatory flow structures are a series of deterministic events. However, the oscillatory events were not totally random in time and space in contrast to the events observed in steady turbulent flow. The oscillatory flow structures exhibited time dependence. The events occurred only during deceleration, and as the flow cycle progressed further in time the events became less frequent and less violent.

The appearance of the flow structures of oscillatory transitional and turbulent flow varied with $N_{Re,u}$ and α . This is fully discussed in the next section. For some values of $N_{Re,u}$ and α , no flow structures were observed and for other values the events were infrequent. Sometimes events in the deterministic sequence were missing and sometimes events were out of order, but the sequence described is the one that was followed on the average. For $N_{Re,u} = 22000$ and $\alpha = 11.60$ (runs 37, 56, and 57 from table 6), all the events were readily observable. Therefore, this set of values of the similarity parameters was used for the description of the oscillatory transitional and turbulent flow structures. All size scales mentioned are for $N_{Re,u} = 22000$ and $\alpha = 11.60$.

The series of events observed in oscillatory transitional and turbulent flow are called retardation, influx, excitation-rotation, discharge, and purge. These names were chosen to avoid confusion with the terms already in common usage in the literature of coherent structures in steady turbulent flow. Different names were chosen because it is uncertain whether the mechanisms causing the events in steady and oscillatory turbulent flow are the same. Comparisons of the individual

events with their counterparts in steady turbulent flow is done in the Comparison of Results section.

Retardation. The first event of the sequence of the flow structures was the retardation. The retardation event was the observation of fluid near the wall moving slower than fluid at a previous time in the same position. In the convective viewpoint, retardation appeared as rapid axial particle motions in the upstream direction at positions closer to the wall than the camera matching position, and as slow downstream motions at positions a little further from the wall than the camera matching position. In a few cases retardation appeared as a pulse of the flow in the wall region. In many cases the retardation event was not observed.

Retardation is not really an extraordinary phenomenon. It can be described as a normal turbulent velocity profile with the region of steep velocity gradient shifted away from the wall (figure 17), possibly an outward shift of the boundary layer. The velocity profile for turbulent oscillatory flow at times around and subsequent to peak velocity (the start of decelerated flow) can be considered like a normal steady turbulent flow velocity profile in a pipe with a steep velocity gradient near the wall and a flat plug flow region in the center. For $N_{Re,u} = 22000$ and $\alpha = 11.60$, the retarded region of the flow extended out to approximately $y^+ = 30$.

No quantitative measurements were made of the retardation event and no dimensions of its position in the flow are presented for other $N_{Re,u}$ and α . Retardation was postulated only from the visual observations of the films. Further proof or disproof of its existence is

Figure 17. Proposed mechanism of the retardation event, comparison of normal and retardation velocity profiles.

necessary. Accurate hot-film anemometry measurements in the wall region are one means to achieve this.

Influx. Just following the retardation event large inflows towards the wall were observed in the flow. This is the influx event. Influxes originated near the outer edge of the wall region ($y^+ = 161$) and at distances much further into the wall region, but never in the retarded region near the wall. Some of the influxes which originated in the inner portions of the wall region penetrated the retarded region as far as a few y^+ units from the wall. The influxes always originated upstream from the retarded region. Influxes interacted with the retarded fluid and accelerated it. A picture of the influx event is shown in figure 18. A possible cause of the influxes is the large velocity gradient in the retarded region combined with the instability of decelerated flow.

The influx event gives some indication of the three-dimensional nature of the flow structures. Many times when the influx event was observed, particles of approximately the same radial position were observed to continue their downstream motions with little radial component towards the wall. This indicates that three-dimensional effects are occurring. This three-dimensional observation also indicates that large velocity gradients may exist between different angular positions.

Excitation-Rotation. The excitation and rotation are actually separate events, but whenever the rotation event was observed it was always at the same time as the excitation event. Both the excitation and rotation events occurred either simultaneously with or directly after the influx event. By this time the retarded region of fluid was

Figure 18. Sketch of the general nature of the influx event.

no longer in the field of view of the camera. The excitation event caused fluid in the wall region to mix, obscuring the retarded region of fluid.

The excitation event is characterized by random chaotic radial motion throughout the entire wall region. The size of the wall region was determined by the distance from the wall undergoing the excitation event and is listed in table 11 for different $N_{Re,u}$ and α . Some individual particle paths for the excitation event from frame by frame plotting are shown in figure 19. These particle paths are at different times, but for the same excitation event. The particle paths are in the convective viewpoint. They illustrate the random chaotic motions which were observed in the wall region.

These random chaotic motions during the excitation event (along with the discharge event) are believed to be involved in the production of turbulence. Some limited evidence of this conclusion was presented in the Preliminary Analysis section. Figures 14 and 15 illustrate the apparent axial and radial rms velocities versus time. The sharp spikes in both the axial and radial rms velocities correspond to points where large amounts of radial motion were observed in the motion pictures.

The rotation event always occurred simultaneously with the excitation event. Some of the excitation events are possibly part of rotations, but if the camera matching velocity in the convective viewpoint is incorrect, it is difficult to observe the rotations. The rotation event was most readily observable when it occurred at the end of an influx. A sketch of the general nature of the excitation-rotation phenomenon is shown in figure 20 and particle paths of two particles

Figure 19. Individual particle paths during the excitation event in the convective viewpoint.

Figure 20. Sketch of the general nature of the excitation-rotation event.

involved in rotations are shown in figures 21a and 22a. The rotation event appeared as a vortex structure which was being convected downstream.

There is no question as to the occurrence of the influx and excitation events. Both are readily observable visually. The calculations of the Preliminary Analysis section reinforce the existence of the excitation event, and the same reasoning applies to the discharge event, too. However, this line of reasoning does not apply to the rotation event. Just because rotation is observed in the convective viewpoint, it does not follow that it truly exists in the flow. Particles which cross the plane of the camera matching position and change direction appear as rotations in the convective viewpoint. The following discussion is an analysis in which the rotation event is observed from three different viewpoints: camera convective, stationary, and vortex convective. The purpose of the analysis is to see if vortex-like motion is observed in all viewpoints.

Three particle paths were chosen for the analysis: two particle paths which appeared to be involved in convective vortices (figures 21a and 22a), and one particle path which did not (figure 23a), although this third particle path had occurred before, during, and after the second vortex (figure 22a). The particle paths in these figures are in the convective viewpoint of the camera. Although physically impossible for this study, it would have been desirable to put these particle paths in the convective viewpoint of the vortex in order to determine if rotational motion was truly occurring. First the camera displacement, L_{cam} , was removed from the particle displacement. This

(a)

(b)

Figure 21. Particle path of a rotation. (a) Camera convective coordinates. (b) Stationary coordinates.

(a)

(b)

Figure 22. Particle path of a rotation. (a) Camera convective coordinates. (b) Stationary coordinates.

(a)

(b)

Figure 23. Particle path during a rotation. (a) Camera convective coordinates. (b) Stationary coordinates.

was done by separating the particle displacement into its apparent axial and radial components, $X_{z,ap}$ and X_r , and adding L_{cam} to $X_{z,ap}$ frame by frame to get X_z . Since the camera moved only axially, X_r was not affected by the convective viewpoint of the camera. The particle paths in stationary coordinates are shown in figures 21b, 22b, and 23b. The observer can understand the shape of these figures to be the general shape of a particle path of a vortex in stationary coordinates by thinking of riding on a particle in a circular vortex in a plug flow. Adding the displacement caused by the plug flow to the displacement caused by the vortex produces the particle path in stationary coordinates. The path for the circular vortex in plug flow will be similar in shape to those of figures 21b, 22b, and 23b.

The next step is to put the particle path in vortex coordinates, riding with the convective velocity of the vortex, and see if the particle rotates. The relationship between velocity in stationary and vortex coordinates is $U_{z,vortex} = U_z - U_{vortex}$, where $U_{z,vortex}$ is the velocity of the particle in vortex coordinates and U_{vortex} is the convective velocity of the entire vortex. Values of U_z can be obtained from frame by frame numerical differentiation of the axial particle path, X_z . However, unlike the camera convective coordinates, it was not possible to measure the displacement of the entire vortex frame by frame to obtain an independent measurement of U_{vortex} . Assumptions about U_{vortex} were made in order to carry out the calculations. The first assumption was that the vortex is convected by a plug flow, making U_{vortex} a constant. Actually, $U_{vortex} = U_{vortex}(r,t)$, but the assumption of no time variation was not too restrictive because a

particle was in view for only a short time. The assumption of no radial variation was also not bad because the vortices were not in a region of steep velocity gradient. The second assumption was that U_{vortex} is the average velocity of the vortex in stationary coordinates for all points in the vortex. In symbols, $U_{\text{vortex}} = \Sigma U_z / n$. The assumption of a convective velocity of the vortex reduced the vortex analysis to a mathematical manipulation. The way that U_{vortex} was chosen assured that the particle would rotate in vortex coordinates. If U_{vortex} could have been measured independently from frame-by-frame plotting of the displacement of the center of the vortex, the particle paths in vortex coordinates would have had physical significance. However, the analysis has been included as an exercise for future calculations of this type. As an aside, the convective velocity of the camera did not appear too different from the convective velocity of the vortex, since the plane of matching velocity in many instances would split the vortex.

The axial displacement of the vortex in vortex coordinates, $X_{z,\text{vortex}}$, was calculated from frame by frame integration of $U_{z,\text{vortex}}$, assuming the vortex started at zero axial displacement. The particle path in vortex coordinates was obtained by plotting $X_{z,\text{vortex}}$ versus X_r since the vortex was observed to be convected only axially.

The particle paths of the three chosen particles in vortex coordinates are shown in figure 24. All three particles exhibited rotation in vortex coordinates, even the one which did not exhibit rotation in camera convective coordinates. Again, this is of dubious significance because the convective velocity of the vortex was not

Figure 24. Particle paths in vortex coordinates. (a) From figure 21. (b) From figure 22. (c) From figure 23.

measurable. However, further evidence of the rotation event is that some rotations were observed outside the camera matching position (for example, figure 22a), and these rotations could not be attributed to a particle appearing to reverse direction because of the convective viewpoint of the camera.

The rotation event like the retardation event was not always observed whenever the flow structures occurred. The occurrence of the rotation event appeared to be dependent on $N_{Re,u}$ and α . Rotations were evident in the runs at $N_{Re,u} = 22000$ and $\alpha = 11.60, 13.40$, and 16.40 and $N_{Re,u} = 14300$ and $\alpha = 9.50$. They were not observable visually for any of the runs at $N_{Re,u} = 11000$ or 7200 .

Discharge. The discharge event like the excitation event is characterized by large amounts of radial motion. However, unlike the random chaotic motions of the excitation event the discharge event is always directed downstream away from the wall, as opposed to the influx event which is directed towards the wall. Two examples of particle paths of discharges in the convective viewpoint are shown in figure 25.

The position of origin of the discharges was anywhere in the wall region and the position of termination was usually outside or in the outer portion of the wall region. The size of the wall region is given in table 11. Discharges which originated closer to the wall also terminated closer to the wall. Discharges were observed to occur at all angles from the wall region, but most of them were observed to be perpendicular to the wall or pointed in the downstream direction in the convective camera viewpoint. Many times discharges were observed to occur at the end of a rotation event.

Figure 25. Individual particle paths during the discharge event in the convective viewpoint.

Discharges appeared to be eddies of low speed fluid (low speed is in reference to the direction of travel of the discharge, away from the wall). The reason the term eddy can be applied to the discharge is that many times only a few tracer particles in a region were observed to undergo the discharge event. The other particles would continue along the paths they were following. Many times it appeared that the discharges were in different planes from the other particles. This is evidence of the three-dimensional nature of the flow structure.

A physical description of the discharge event is that it is a low speed eddy, pointed in the downstream direction in the convective viewpoint, with a large acceleration in the radial direction. As the eddy moves away from the wall it loses its radial acceleration and interacts with the fluid in the region it is moving into. The eddy is then accelerated axially by the faster moving fluid and mixes totally with the fluid at a further distance from the wall than where it originated. This is a suggested mechanism for the production of turbulence near the wall and its transfer to the mean flow. Axial and radial rms velocities during the discharge event, figures 14 and 15, support this statement.

Purge. The purge event is simply the return of the flow field to basically rectilinear motions until the next sequence of events. For the more turbulent states (higher $N_{Re,u}$), there were multiple occurrences of the influx, excitation-rotation, and discharge between purges. This is either because purges did not occur between the other events or the purges were so rapid that they were not observable. The purge event

may be associated with a relaminarization effect. This conclusion is backed up by the fact that purges were more readily observable for the lower $N_{Re,u}$.

Coherence. Each event observed in oscillatory transitional and turbulent flow has been discussed individually. In this section, the coherent nature of the events is discussed. Some physical explanation about the mechanism of the occurrence of the events is offered, but due to the limited amount of information available from this investigation, the explanations are mainly conjecture.

The fact that the events are linked to each other in a coherent manner was demonstrated by the observation that, on the average, the events followed a deterministic sequence. First, the retardation event was observed followed by the influx event. Influxes interacted with the retarded region of fluid and then the excitations and rotations occurred in the wall region. During the time that the wall region was in an excited state the discharge event was observed. Finally, the reestablishment of rectilinear motion was observed with the purge event. A physical picture of the influx, excitation-rotation and discharge is shown in figure 20.

The mechanism of transition to turbulence is not well understood. However, it is known that inflection points in a velocity profile may cause instabilities in a flow. The retardation event is the observation of low speed fluid in the wall region compared to a previous time. This suggests the possibility of an inflection point in the velocity profile. Inflection points are also suggested by the change from

acceleration to deceleration in oscillatory flow. The effect of viscosity is to damp out instabilities or to eliminate the inflection point. However, for certain values of the similarity parameters, the instabilities will dominate the viscous effects and the flow will undergo transition to turbulence.

Two types of instabilities have been observed for steady flow. The first is a wave instability (Tollmien-Schlichting type), and the second is a rotational instability (Kelvin-Helmholtz type). A wave instability and its growth in time is a possible cause of the excited radial motions observed with the excitation event. The rotation event of oscillatory flow gave an indication of a rotational instability, but a rotational instability cannot be associated with the rotation event of this investigation because an inflection point in the velocity profile would cause rotations in the opposite direction of some of those rotations observed in the motion pictures.

During the influx, excitation, and discharge events, the wall region is observed to undergo radial motions. The influx event is directed primarily towards the wall while the discharge event is directed primarily away from the wall. This suggests some sort of continuity mechanism. However, continuity alone does not offer a completely satisfactory explanation because the discharge event appeared more violent (higher velocity) than the influx event. This means that the influx event should be of a large size scale (larger area) than the discharge event. This was not observed in the motion pictures.

Frequency Parameter and Reynolds Number Effects

With the establishment of coherent flow structures for transitional and turbulent oscillatory flow, it was possible to determine how these flow structures varied with $N_{Re,u}$ and α . This was accomplished by two means. First, the variation of the flow structures with $N_{Re,u}$ and α was observed in the motion pictures by comparing runs with either $N_{Re,u}$ or α held constant and the other parameter variable. Qualitative conclusions as to whether the flow was turbulent and the degree of turbulence according to the flow structures were made. These qualitative conclusions were then plotted against $N_{Re,u}$, α , $N_{Re,\delta}$ ($N_{Re,\delta} = N_{Re,u}/\alpha\sqrt{2}$, $\delta = \sqrt{2\nu/\omega}$), and $N_{Re,\delta}/\alpha$.

Three criteria were used in determining the qualitative variation of the flow structures with $N_{Re,u}$ and α . First, the motion pictures were studied for visual evidence of the flow structures. For some combinations of $N_{Re,u}$ and α , no flow structures at all were observed, only rectilinear flow. It cannot be stated whether the cases of no observed flow structures were truly laminar, transitional, or turbulent. For the cases which did exhibit flow structures, more quantitative evidence of the variation of the flow structures with $N_{Re,u}$ and α is presented. Observations of the amount and severity of the radial motions of the tracer particles were compared for runs with one parameter held constant and the other one variable. The frequency of occurrence of events was considered as the third criterion. It was rejected because the occurrence of the flow structures was time-dependent, and it was difficult to always distinguish where one event began and another ended. However, the time dependence itself was used

as a criterion in determining the degree of turbulence according to the flow structures. It was observed that for different combinations of $N_{Re,u}$ and α , the first appearance of flow structures occurred at different points in the flow cycle. The earliest time when events were evident in any motion picture for a set of $N_{Re,u}$ and α was used as a measure of turbulence. The time into the cycle where flow structures first appeared was normalized by the period of the cycle. The shorter this normalized time was, the more turbulent the flow was considered. This argument follows the argument of Yellin (85) that the longer and further a flow is in a region below its $N_{Re,c,ave}$, the more time there is for turbulence to be dissipated. The argument here is that the longer and further an oscillatory flow is in a turbulent regime, the sooner the turbulence will manifest itself.

Frequency Parameter Effect. Three values of $N_{Re,u}$ were held constant while α was varied. They were $N_{Re,u} = 22000$, $\alpha = 16.40$, 13.40, and 11.60; $N_{Re,u} = 11000$, $\alpha = 11.60$, 9.50, and 8.10; and $N_{Re,u} = 7200$, $\alpha = 9.50$, 7.75, and 6.65.

For $N_{Re,u} = 22000$, all three values of α investigated exhibited all the events. However, all three α were not equivalent. As α increased from 11.60 to 13.40 and again from 13.40 to 16.40, the severity of the events as observed by the amount and activity of the radial motion of the tracer particles in the wall region decreased. For $\alpha = 13.40$ and $\alpha = 16.40$, the frequency of discharges for the time the flow structures were evident was smaller than for $\alpha = 11.60$. The times at which the events first manifested themselves, expressed as a fraction

of the time into the flow cycle, were .48, .58, and .81 for $\alpha = 11.60$, 13.40, and 16.40, respectively.

For $N_{Re,u} = 11000$ and $\alpha = 11.60$, no flow structures were observed. The runs at $N_{Re,u} = 11000$ and $\alpha = 9.50$ and 8.10 both showed events. Comparing these two runs, the amount of radial activity decreased as α was increased from 8.10 to 9.50. The runs at $N_{Re,u} = 11000$ and $\alpha = 8.10$ appeared equivalent to the runs at $N_{Re,u} = 22000$ and $\alpha = 11.60$. The fraction of time into the flow cycle where the flow structures were first evident was less for the smaller α at $N_{Re,u} = 11000$. The values were .48 and .59. These results were consistent with those for $N_{Re,u} = 22000$.

For the lowest $N_{Re,u}$ studied, $N_{Re,u} = 7200$, and $\alpha = 9.50$ there was no observed evidence of flow structures. The other points, $N_{Re,u} = 7200$ and $\alpha = 7.75$ and 6.65, were strikingly similar. The amount of observed radial motion was the same in both runs, and so was the fraction of time into the cycle when the flow structures first appeared, .67.

The conclusion is that the level of turbulence as observed through the flow structures decreases with increasing α , all other things being constant. This agrees with a physical interpretation where α is considered the ratio of the time of a cycle ($1/\omega$) to the time necessary for the amplification of disturbances (R^2/ν). If α is increased, the time of a cycle is decreased and less time is available for amplification of disturbances. Therefore, increasing α should lead to a stabler state of the flow if all other things are

equal. This is what was observed for all three cases where $N_{Re,u}$ was held constant and α was varied.

The limited amount of data also implied two other effects of frequency. First, the size scale of the flow structures (table 11) increased with decreasing α for $N_{Re,u} = 22000$ and 11000. No conclusion can be drawn about the size scale for $N_{Re,u} = 7200$ because only two points exhibited flow structures, and the size scales measured were equal to each other within experimental error. Secondly, a value of α where the flow structures were unaffected by frequency was implied by the equivalent normalized times of the first appearance of the flow structures for $N_{Re,u} = 7200$ and $\alpha = 7.75$ and 6.65. This is evidence of a quasi-steady state for transitional and turbulent oscillatory flow.

Reynolds Number Effect. Two values of α were held constant while $N_{Re,u}$ was varied. They were $\alpha = 11.60$, $N_{Re,u} = 11000$, 16300, and 22000; and $\alpha = 9.50$, $N_{Re,u} = 7200$, 11000, and 14300.

For $\alpha = 11.60$, two values of $N_{Re,u}$ showed no flow structures. They were $N_{Re,u} = 11000$ and 16300. The other point, $N_{Re,u} = 22000$, was turbulent according to the flow structures. The first observation of the flow structures was seen at .48 into the flow cycle.

For $\alpha = 9.50$ and $N_{Re,u} = 7200$, no flow structures were observed again. For $\alpha = 9.50$ and $N_{Re,u} = 11000$ and 14300, events were observed. A comparison of the two runs showed that there was more radial activity more often for $N_{Re,u} = 14300$ than for $N_{Re,u} = 11000$. The times of first appearance of the flow structures also pointed to a more turbulent state for $N_{Re,u} = 14300$. They were .59 for $N_{Re,u} = 11000$ and .45 for $N_{Re,u} = 14300$.

The conclusion is that the level of turbulence as observed through the flow structures increases with increasing $N_{Re,u}$ all other things being equal. This conclusion agrees with the physical interpretation of $N_{Re,u}$ as the ratio of the inertial to viscous forces. As $N_{Re,u}$ is increased so are the inertial forces which tend to destabilize the flow and lead to a turbulent state.

The size scale of the flow structures (table 11) increases with increasing $N_{Re,u}$. However, there was only one point of comparison at constant α , $\alpha = 9.50$ and $N_{Re,u}$ changing from 11000 to 14300. If paths of constant α are not followed, the general trend is also increasing size scale for increasing $N_{Re,u}$. This is seen by comparing the average size scales for $N_{Re,u} = 7200$, 11000, and 22000.

Combined Effects. Figure 26 is a map of the state of the flow according to the flow structures versus $N_{Re,u}$ and α . The points with dark circles showed evidence of flow structures at some point in the flow cycle during decelerated flow and are considered turbulent. The points with the open circles showed no evidence of the flow structures at any time in the cycle, and are called undisturbed. No conclusion was made whether the points of no flow structures were laminar, transitional, or turbulent.

Figure 26 graphically illustrates the variation of the flow structures with $N_{Re,u}$ and α . If α is increased along a path of constant $N_{Re,u}$, values are reached where no flow structures occurred. The same is true if $N_{Re,u}$ is decreased along a path of constant α . The values of the fraction of time, normalized by the period of the cycle, where the flow structures first appeared are also listed to distinguish

Figure 26. State of the flow according to the flow structures versus $N_{Re,u}$ and α . ●, turbulent, ○, undisturbed. The superscript number is the normalized time of the first appearance of the flow structures.

Figure 27. State of the flow according to the flow structures versus $N_{Re,\delta}$ and α . ●, turbulent, ○, undisturbed.

Two other points about the upper and lower limits of $N_{Rec,\delta}$ will be discussed. The lowest turbulent point was $N_{Re,\delta} = 657$. However, the point of no flow structures closest in value to the lowest turbulent point was $N_{Re,\delta} = 671$. Referring back to table 6 (the actual values of $N_{Re,u}$ and α for the experimental runs) and recalculating $N_{Re,\delta}$ for these two points, the lowest turbulent point was $N_{Re,\delta} = 667$ and 663 , while the closest point of no flow structures to the lowest turbulent point was $N_{Re,\delta} = 672$ and 661 . Therefore, an approximate lower limit of $N_{Rec,\delta} = 650$ was chosen. The highest point of no flow structures, $N_{Re,\delta} = 994$, seems out of place. If this point was turbulent, a constant value of $N_{Rec,\delta}$ could be postulated from the data. One explanation for the out of place data point is that the critical Reynolds number is the point where a flow may go turbulent but does not necessarily have to depending on other circumstances. The other explanation is that there were flow structures, but the camera was not in the correct position at the correct time to perceive them since the flow structures are random in space. The second explanation is believed to be true. Actually this explanation can be extended to all the points of no flow structures since it is very difficult to prove conclusively that no flow structures exist for a given combination of $N_{Re,u}$ and α . Considering these uncertainties, the best estimate of $N_{Rec,\delta}$ as determined from the flow structures is in the range from 650 to 1000.

In the Theoretical Basis section, a linear relationship, $N_{Rec,u} = K\alpha$ was shown (equation (21)). The constant, $K = N_{Rec,\delta}\sqrt{2}$. Using $N_{Rec,\delta}$ determined from figure 27, K ranges between 920 and 1415.

The limiting values are plotted in figure 26. Both values of K misrepresent some of the data points because of the uncertainty in $N_{Re,\delta}$.

Plots of the time of first appearance of the flow structures versus $N_{Re,\delta}$ and $N_{Re,\delta}/\alpha$ (figures 28a and 28b) are presented to see if the time of first appearance correlated into one curve with a limiting value of one. This was not the case for figure 28a, but each constant $N_{Re,u}$ and α value has a curve of its own with a limiting value of one. The plot of $N_{Re,\delta}/\alpha$ (figure 28b) did not correlate either. This means that there are other variables besides $N_{Re,\delta}$ and $N_{Re,\delta}/\alpha$ which control the stability of the flow. Both figures again illustrate the dependence of turbulence on $N_{Re,u}$ and α .

(a)

(b)

Figure 28. Normalized time of the first appearance of the flow structures. (a) Versus $N_{Re,\delta}$. (b) Versus $N_{Re,\delta}/\alpha$.

COMPARISON OF RESULTS

The experimental results of this study are compared with the results of previous investigators from the literature. Only results pertinent to this study are compared. A more extensive survey of the literature of transitional and turbulent pulsatile flow was presented in the Literature Review section.

Steady Turbulent Flow Structures

Since the experimental technique of this study was the same as that used by Corino and Brodkey (10), Corino (11), and Nychas, Hershey, and Brodkey (52), all comparisons between the steady and oscillatory flow structures are made between these works and this study. The work of Corino and Brodkey (10, 11) is especially important for it was also carried out in a pipe flow. Comparisons between the coherent flow structures of these authors (10, 11, 52) and other studies on the steady turbulent flow structures can be found in these papers and also the dissertation of Praturi (57). General comparisons between the steady and oscillatory flow structures are reviewed and then the oscillatory events are compared to their counterparts in steady turbulent flow. The names chosen for the oscillatory transitional and turbulent events were different than those in current usage for their counterparts in steady turbulent flow to avoid suggesting the same mechanism must

necessarily apply. Table 12 is a comparison of the terminology used for the steady turbulent flow structures with that selected for the oscillatory structures.

Both the oscillatory transitional and turbulent coherent flow structures and the steady turbulent coherent flow structures were characterized by a series of similar deterministic events and both randomly occurred in space. The transitional and turbulent oscillatory coherent flow structures were dependent on time, occurring only during decelerated flow. In contrast, the steady turbulent coherent flow structures occurred randomly in time.

Comparisons of the flow structures depend on how they are observed. Therefore, a digression to discuss the field of view of the camera in the experiments of interest and how the flow field was divided into regions is discussed in the next two paragraphs. The field of view of the camera (figure 9) in the radial direction (rz plane) for this study was over 4.5X that of Corino and Brodkey (10) in a 5.08 cm (2 in.) ID pipe. The view of Nychas et al. (52) on a flat plate was 10X that of this study. This means that the same events in these studies may be viewed differently because of their different sizes.

In the steady turbulent flow studies, the field of view was divided into regions according to how the observed properties of the flow varied with distance from the wall. Corino and Brodkey (10) used three regions called sublayer region ($0 < y^+ < 5$), generation region ($5 < y^+ < 70$), and core region ($y^+ > 70$). Nychas et al. (52) with a larger field of view used two regions called wall region ($0 < y^+ < 70$)

Table 12

Comparison of Terminology Between the Oscillatory
and Steady Flow Structures

<u>Event in Oscillatory Flow</u>	<u>Equivalent Event in Steady Flow</u>
retardation	deceleration
influx	acceleration
excitation	-----
rotation	transverse vortices
discharge	ejection
purge	sweep

and outer region ($y^+ > 70$). In this study, no intermediate distinctions were made between the flow properties and the distance from the wall and the flow field was divided into two regions, a wall region and an outer region. The distinction between the two regions was that the wall region was the area of chaotic radial motions while the outer region exhibited mainly rectilinear flow. Sizes of the wall region are listed in table 11. The largest value was $y^+ = 161$ for $N_{Re,u} = 22000$ and $\alpha = 11.60$. The size of the wall region was observed to change with $N_{Re,u}$ and α for oscillatory flow. No variation with Reynolds number for the size of any of the regions was reported for steady flow. Corino and Brodkey (10) studied $N_{Re,ave}$ between 2300-52000, but all their descriptions are for $N_{Re,ave} = 20000$. Nychas et al. (52) studied only one Reynolds number.

The retardation event is similar to the deceleration event of steady turbulent flow. In all cases a region of slow moving fluid was observed. In this study and the study of Corino and Brodkey (10) the event occurred near the wall. An estimate of the size of the region from the wall where the deceleration event for $N_{Re,ave} = 20000$ was observed was given as $y^+ = 30$ (10). The retardation event was also observed to occur out to positions of $y^+ = 30$ from the wall for $N_{Re,u} = 22000$ and $\alpha = 11.60$. The retardation event did not appear as drastic as the deceleration event. This is possibly because the deceleration event occurred in a region where the whole flow field was undergoing deceleration.

The next events in oscillatory and steady flow, influx and acceleration, are also very similar. The major difference was that the

influx was of a much smaller size scale than the acceleration. The acceleration event covered the whole field of view in the study of Corino and Brodkey (10). Influxes were small volumes of fluid (like an eddy) which moved together downstream and towards the wall. Influxes are very similar to the large inflows observed by Nychas et al. (52) except that influxes penetrated nearly to the wall while the large scale inflows were associated with the outer region of the boundary layer flow.

The excitation event does not have an analogous counterpart in steady turbulent flow except for the generally nonrectilinear flow observed by Corino and Brodkey (10) and Nychas et al. (52) throughout the flow field. The only comparison between the excitation event is made for distances very near the wall. Small scale velocity fluctuations are observed in the sublayer region by Corino and Brodkey (10). They also observed that the small scale fluctuations did not occur for $y^+ < 2.5$. In this study, the excitation event extended all the way to the wall because particles were observed to strike the wall.

The rotation event of the oscillatory flow structures is similar to the transverse vortices reported by Nychas et al. (52). Corino and Brodkey (10) did not report any rotational motions in their study. In this study and the work of Nychas et al. (52), the rotations and transverse vortices were observed to occur at the end of the influxes and accelerations. The transverse vortices of Nychas occurred in the outer region, y^+ between 100-400, while the rotations of this study occurred closer to the wall, centered around $y^+ = 30$, and were of a smaller size. In both cases, the rotations and transverse vortices

were closely associated with the next step in the sequence of the flow structures, the discharge and ejection. Ejections were observed as the transverse vortex was transported downstream. In this study, discharges were sometimes observed to occur at the end of rotations. Corino and Brodkey (10) suspected that the rotations occurred in their experiments, but did not observe any. However, they suggested that the rotations were part of an instability mechanism of the laminar-turbulent transition and gave rise to the ejections. The rotations in oscillatory flow were also believed to be involved in the laminar-turbulent transition process, especially since the oscillatory flow studied is a transitional problem. Nychas et al. (52) suggested that the transverse vortices were involved in the transfer of energy from and to the wall region. This also is believed to be a function of the rotations.

The discharges in oscillatory flow and the ejections in steady flow are believed to be the major contributors to the production of turbulence near the wall. Corino and Brodkey (10) calculated that ejections accounted for 70% of the Reynolds stress ($u_r u_z / U^*{}^2$). Nychas et al. (52) reported that the instantaneous Reynolds stress for ejections is much larger than the corresponding mean local values. In this study, the radial and axial rms velocities (u'_r, u'_z) were shown to have sharp spikes which correspond to the discharges and also the excitations. The major difference between ejections and discharges is their points of origin. Ejections were observed to originate in the decelerated region. Discharges originated anywhere in the wall region.

The purge event of this study and the sweep event of Corino and Brodkey (10) are again very similar. They are both characterised by

the return of the flow field to a somewhat normal velocity profile. In oscillatory flow, basically rectilinear motions were observed after the purge event, and this may be associated with a relaminarization effect. Nychas et al. (52) concluded that the sweep event was also a contributor to turbulence energy production from the calculation of instantaneous Reynolds stress.

Transition and Turbulence

In the Experimental Results section, it was demonstrated that according to the flow structures turbulence decreases with increasing α and increases with increasing $N_{Re,u}$ for oscillatory flow. A range of the critical Reynolds number for the transition to turbulence based on Stokes layer thickness, $N_{Re,\delta}$, was calculated according to the flow structures. These results are compared with the results from the literature in this section.

The fact that turbulence increases with increasing Reynolds number is a well established fact and needs no further discussion. The variation of turbulence with α has some ambiguities and warrants further discussion. Nerem, Seed, and Wood (50), in an in vivo study using dogs, found that $N_{Rec,u} = K\alpha$. The criterion they used to determine turbulence was the amount of disturbance in a velocity waveform. Clarion and Pelissier (9), from a study of oscillatory pipe flow, proposed that $N_{Rec,u} = K\alpha^{0.8}$. It is noted that both Nerem et al. and Clarion and Pelissier were not certain if they observed turbulence, but they did observe what they called highly disturbed flows which may have been turbulent. This study, because of the similarities between

the steady and oscillatory flow structures, indicates that turbulence was observed in most cases. Both the study of Nerem et al. and Clarion and Pelissier corroborate the findings of this study that turbulence decreases with increasing α . This is seen from the relationships between $N_{Rec,u}$ and α because if α is increased it takes a larger value of $N_{Re,u}$ to attain a turbulent state. However, contradictory results of the variation of turbulence with α are found in the pulsatile flow (mean flow superposed on an oscillatory flow) investigations of Gilbrech and Combs (22) and Sarpkaya (62). Both studies indicate that for fixed U_{amp} , $N_{Rec,ave}$ decreases as α is increased. This means that if α is increased turbulence is possible for lower $N_{Re,ave}$. The results of Gilbrech and Combs (22) and Sarpkaya (62) suggest that the presence of a mean flow changes the character of the transition to turbulence.. However, they studied U_{amp} only between 0-1, which are oscillatory flows of at most the same order of magnitude as the mean flow.

The critical Reynolds number based on Stokes layer thickness, $N_{Rec,\delta}$, was found to be in a range from 650 to 1000 in this study. Two other investigators reported values of $N_{Rec,\delta}$ for oscillatory flow in pipe geometry. Sergeev (70) used flow visualization and measurements with a strain gauge to obtain a value of 495. Hino, Sawamoto, and Takasu (27) reported a value of 550 using hot-wire anemometry. Both of these studies reported values somewhat lower than the values found in this study. One explanation for the discrepancies is that different experimental setups and techniques give different results because of the different disturbance levels in each. An explanation for the high upper limit for this study was either that the camera was not in the

correct place at the correct time to observe flow structures or the flow was just not turbulent for the experimental runs taken. However, the fairly good agreement of the value of $N_{Rec,\delta}$ between this study and others of the same geometry and flow pattern shows that the flow structures are a good indicator of turbulence.

In one paper, two types of transition for oscillatory flow were observed to exist. The first type of transition, observed by only Hino et al. (27), was characterized by small scale disturbances observed throughout the laminar velocity profile. The second type of transition, followed by relaminarization, occurred only during decelerated flow, and was observed by most investigators of transition in oscillatory flow. Transition followed by relaminarization was the only type of transition observed in this study. Transition of the first type occurred at lower values of $N_{Re,u}$ than the second type. However, Hino et al. (27) studied lower $N_{Re,u}$ and only the lowest values of α ($N_{Re,u} = 105-5830$, $\alpha = 1.91-8.75$) covered in this study ($N_{Re,u} = 7200-22000$, $\alpha = 6.65-16.40$). Whether the flow structures would indicate the first type of transition is a subject for further investigation.

In turbulent pulsatile flow, two relationships for a critical value of α where the flow changes from a quasi-steady state to an oscillatory form were proposed. Lu, Nunge, Erian, and Mohajery (40) proposed that for a quasi-steady state, $0.025 \times N_{Re,ave} > \alpha^2$. Mizushima, Maruyama, and Shiozaki (46) proposed that $\alpha_c^2 \approx 8.27 \times N_{Re,ave}^{1/3}$. In this investigation, all the values of the similarity

parameters studied were in the quasi-steady state according to the relationship of Lu et al. (40) and only the runs at $N_{Re,u} = 22000$ and $\alpha = 16.40$ were outside the quasi-steady state according to the relationship of Mizushima et al. (46). However, the general nature of the flow structures showed no alteration between the one point outside the quasi-steady state according to Mizushima et al. (46) and the others. Note should be taken that these relationships for transition between a quasi-steady state and an oscillatory state are for fully turbulent pulsatile flow. The basis of comparison between this oscillatory flow transitional and turbulent study and the quasi-steady state relationships is not one to one. In general, the events were all of the same nature and no critical value of α was observed. The only evidence of a quasi-steady state was identical flow structures for the runs at $N_{Re,u} = 7200$ and $\alpha = 7.75$ and 6.65 . The normalized time of first appearance of the flow structures was .67 for each case.

Oscillatory Flow Visual Studies

Merkli and Thomann (44) using flow visualization by smoke in oscillatory pipe flow found persistent vortices along the pipe wall for laminar flow. Using the disappearance of the vortices as the criterion of transition to turbulence they found that $N_{Rec,\delta} = 283$. It is believed that the rotation event is not similar to the vortices of Merkli and Thomann (44) because of a difference in the experimental setup and especially because they occur in laminar flow and disappear with turbulence. Merkli and Thomann used a resonance tube and one end of the tube was closed. The value of $N_{Rec,\delta}$ which is lower than other

oscillatory pipe flow experiments points to some sort of disturbance imposed by the experimental setup. Merkli and Thomann suggested that the wall waviness of their plexiglass tubes may have been a cause of the vortex formation in their study.

Clarion and Pelissier (9) also observed vortices in oscillatory pipe flow with a flow visualization technique. These vortices were also not associated with the rotation event because they were reported to fill the whole cross section of the tube. Rotations were associated with a region near the pipe wall.

CONCLUSIONS

The experimental results of this investigation lead to the following conclusions.

1. There are coherent structures of oscillatory transitional and turbulent flow which are observable by the flow visualization technique used in this study.
2. The coherent structures of oscillatory transitional and turbulent flow exhibit many similarities to the coherent structures of steady turbulent flow. Both the oscillatory and steady coherent structures are characterized by a series of deterministic events. Each individual event has its counterpart (retardation:deceleration; influx:acceleration; rotation:transverse vortices; discharge:ejection; and purge:sweep). Both the oscillatory and steady flow structures occur randomly in space. However, the oscillatory transitional and turbulent flow structures are time-dependent, occurring only during decelerated flow, while the steady turbulent flow structures are random in time. The similarities between the oscillatory and steady events indicate that it was turbulence which was observed in oscillatory flow.

3. The most important events observed in oscillatory transitional and turbulent flow are the excitation-rotation and discharge. The excitation and discharge events are believed to be involved in turbulence generation in the wall region. The rotation event is believed to play an important role in the laminar-turbulent transition process.
4. The oscillatory transitional and turbulent flow structures are a function of $N_{Re,u}$ and α . Therefore, the level of turbulence is also a function of $N_{Re,u}$ and α . The activity and time of first occurrence of the flow structures in the cycle shows that turbulence increases with increasing $N_{Re,u}$ and decreases with increasing α . There were also combinations of $N_{Re,u}$ and α where no flow structures at all were observed.
5. From a plot of $N_{Re,\delta}$ versus α , a value of $N_{Rec,\delta}$ between 650-1000 was determined. This value of $N_{Rec,\delta}$ is in good agreement with other values in the literature and shows that the oscillatory transitional and turbulent flow structures are a good indicator of whether the flow is laminar or turbulent.

RECOMMENDATIONS

The recommendations which come out of this study are of three types. They include equipment improvement, further study of the flow structures, and further study of the transition to turbulence and the turbulent state in oscillatory and pulsatile flow through flow visualization and other means.

1. Improve the equipment used to generate an oscillatory flow and move the camera in phase with the flow. This could be done by separating the scotch yoke from the gearing system and coupling the two together by electronic means (a controller possibly). A hydraulic system like the one developed for steady flow (11) could be developed to move the camera sinusoidally. The scotch yoke and piston and cylinder should be redesigned to enable lower and higher $N_{Re,u}$ and α combinations to be studied. Possibly different size scotch yokes (or piston and cylinders) should be used to allow for the study of a much wider range of $N_{Re,u}$ and α . The scotch yoke, flywheel, drive system, piston and cylinder, and gearing system (if necessary) should all be assembled on a single base which allows for adjustment of the components with respect to one

another. After the system is set up, the camera carriage should be checked to see that the camera does not vibrate. The flow should also be checked and compared with other results to see if it is oscillatory and turbulent. Hot-film anemometry measurements should be satisfactory for checking.

2. The study of the flow structures of transitional and turbulent oscillatory flow should be extended to lower and higher values of $N_{Re,u}$ and α . The purpose of this is to determine if the flow structures are an indicator of a quasi-steady state for transitional or turbulent flow, and to improve upon the lower limit of $N_{Rec,\delta}$, which is an indication of the point of transition to turbulence, determined in this study.
3. In order to make better comparisons with in vivo arterial flow work, the study of the flow structures should be extended to include entrance effects and a mean flow superposed on the oscillatory flow. In terms of equipment, entrance effects should cause no problems. The photographic system would remain intact and only the front entry section would have to be removed from the pipe unit. One means of adding a mean flow to the present system is to use a constant head tank with recycle. The scotch yoke would still provide the oscillatory motion.

In the case of a mean flow superposed on an oscillatory flow, the photographic system would have to follow both the oscillatory and steady motions. Perhaps another means of locomotion for the photographic system would have to be designed.

4. The study of the excitation-rotation and discharge events by hot-film anemometry methods to get quantitative results on their contribution to turbulence generation is another worthwhile study. This may be accomplished by combining the visual technique used in this study with hot-film anemometry work and using some sort of conditional sampling when the excitation-rotation and discharge events are in view. Verification of the retardation event would also be desirable.
5. Like the flow visualization studies of steady turbulent flow, the oscillatory transitional and turbulent flow structures are three-dimensional. Three-dimensional information on the flow structures may be achieved by using a three-dimensional photographic technique, hot-film anemometry, or a combination of these. Another means to gain limited three-dimensional information using the visual technique of this study is to change the position of the camera view. Setting the camera directly above the pipe axis and focusing at

a position near the wall would essentially provide a view of the $z\theta$ plane. Comparisons of the rz plane view of this study with the $z\theta$ plane should provide some three-dimensional information. A view of the $r\theta$ plane is impossible to get with the present equipment, since it would entail placing the camera inside the pipe.

APPENDIX A

EQUIPMENT DESIGN

In this section, details of the design of some of the experimental equipment is presented. Some equipment was available from previous work and some equipment was salvaged from scrap supplies. The specifications of the available equipment set many of the geometric constraints of the system. The choice of TCE as the test fluid set the physical properties. Reference should be made when reading this section to the Materials and Equipment section for all specifications not mentioned in this section. All design calculations were done at 25°C.

Experimental Criterion

For an initial visual study on oscillatory flow, a simple flow system was required so that the results could be interpreted. Simple is used in this case to mean as few complexities in the flow pattern as possible. The geometry chosen was a straight, smooth, rigid, circular pipe of constant cross section. The flow was designed to be purely oscillatory (no mean flow), and the flow driving force a simple harmonic motion. This led to the choice of a scotch yoke and flywheel.

The flow was designed to be fully developed. Originally, a mean flow was to be included. The first part of the entry length discussion includes mean flow effects. In the next paragraph, the concept

of entry length for purely oscillatory flow is discussed. For laminar pulsatile flow, Chang and Atabek (7) recommended an equation for the entry length as

$$L = 0.08 R N_{Re,ave} \quad (1)$$

For $N_{Re,ave} = 4000$, equation (1) gives an entry length of 406.4 cm. Entry lengths of 701.0 cm and 609.6 cm were provided. The effect of frequency parameter as proposed by McDonald (43) is that "the higher the value of α the shorter one would expect the oscillatory inlet length to be." Chang and Atabek (7) used $\alpha = 4$ in their calculations. This gives greater confidence that sufficient entry length has been provided since higher values of α were investigated. For turbulent flow, no analytical relation for either pulsatile, or oscillatory flow exists for the entry length, but experiments (17, 34, 51) have shown that a rule of thumb is that a minimum of 40 pipe diameters downstream is needed for fully developed steady turbulent flow (28). This criterion was used here since most of the motion pictures were taken in the quasi-steady regime of turbulence. Entry lengths of 276.0 and 240.0 pipe diameters were provided.

For oscillatory flow, the concept of a fully developed velocity profile is somewhat nebulous when using steady flow definitions. A good definition of entry length for oscillatory flow in this investigation is enough length so that the maximum fluid travel in half a cycle (X_{max}) does not exceed the length of smooth pipe provided on either side of the section of interest (the visual test section in this

study). In symbols this is expressed as $X_{\max} \ll L$. An estimate of $X_{\max}$ is calculated in the next subsection and values are presented in figure 29. The largest value of $X_{\max}$ studied was 205.74 cm ($X_{pis} = 10.16$ cm). Therefore, $X_{\max}$ was much smaller than either the 701.0 cm or 609.6 cm of entry length provided.

Values of the similarity parameters, $N_{Re,u}$ and α , in the range of

$$N_{Re,u} \approx 4000-20000$$

and

$$\alpha \approx 0.0-20.0 \text{ were considered.}$$

This included values in the normal human physiological range (43) and in the quasi-steady and intermediate frequency regimes of turbulence according to the relation proposed by Lu et al. (40).

The last criterion is the convective viewpoint of the camera. The camera should be moved in phase with the flow driving force, but with variable displacement to match the fluid velocity at various radial positions. This led to the choice of the gearing system. The equations used to design the scotch yoke, flywheel, and gearing system are presented in the ensuing subsections.

Design-Scotch Yoke and Flywheel

The purpose of the scotch yoke and flywheel was to provide a simple harmonic motion driving force to the fluid by translating a circular motion into a linear motion. This is stated mathematically as

$$U = U_u = U_{u,\max} \sin(2\pi t/T) \quad (2)$$

Figure 29. Maximum fluid travel versus $N_{Re,u}$ and α .

since the radial dependence of the velocity profile is uniform at the entrance. Downstream a velocity profile develops and is represented as

$$U = U_u(r, t). \quad (3)$$

However, for the design calculations it was assumed that a velocity profile of the form

$$U = U_{u, \max}(r) \sin(2\pi t/T) \quad (4)$$

is appropriate for every radial position and at the centerline

$$U = U_{u, \max} \sin(2\pi t/T). \quad (2)$$

This is not too bad an assumption for turbulent flow because the velocity profile tends to remain somewhat flat as in the entry section. The other major assumption made in the design calculations is the use of steady flow turbulence relations. This assumption is justified for most of the similarity parameters used by the empirical relation proposed by Lu et al. (40) for the range of similarity parameters where quasi-steady turbulence is appropriate and is

$$0.025 N_{Re, ave} > \alpha^2. \quad (5)$$

For smaller Reynolds numbers, the problem is one of transition, but steady flow turbulence relations were still used for the design calculations.

A basic relationship from dynamics which relates displacement and instantaneous velocity is

$$U = \frac{dX}{dt}. \quad (6)$$

At the centerline, equation (2) represents the instantaneous velocity so

$$U_{u,max} \sin(2\pi t/T) = \frac{dX}{dt}. \quad (7)$$

Equation (7) can be integrated over half a cycle as follows

$$\int_0^{X_{max}} dX = U_{u,max} \int_0^{T/2} \sin(2\pi t/T) dt \quad (8)$$

or

$$X_{max} = U_{u,max} T/\pi. \quad (9)$$

Equation (9) represents the distance the fluid travels in half a cycle at the centerline or its maximum travel. The definitions of Reynolds number and frequency parameter are

$$N_{Re,u} = D U_{u,max}/\nu \quad (10)$$

and

$$\alpha = R\sqrt{\omega/\nu}. \quad (11)$$

Equations (9), (10), and (11) were solved simultaneously for X_{max} by choosing values of $N_{Re,u}$ and α (see figure 29).

The equation of continuity for an incompressible fluid states that

$$U_{ave1} A_1 = U_{ave2} A_2. \quad (12)$$

Since maximum and average velocity are directly related, equation (12) can be rewritten as

$$U_{u,max1} A_1 = U_{u,max2} A_2 \quad (13)$$

With the aid of equation (9) and the definition of A, the relation between fluid displacement at the centerline and piston stroke length is

$$X_{max} D^2 = X_{pis} D_c^2 \quad (14)$$

where X_{pis} is the piston stroke length necessary to obtain a chosen combination of $N_{Re,u}$ and α (see figure 29) and D_c is the cylinder diameter. The piston stroke length is exactly equal to the displacement of the scotch yoke during half a cycle and also equal to the flywheel diameter setting. The flywheel speed (rpm) is directly related to α (see figure 30). From X_{pis} and rpm the scotch yoke and flywheel were designed.

Design-Gearing System

Due to the effect of viscosity, fluid in regions closer to the wall had a shorter displacement (slower velocity) than fluid at the centerline for the same period. The purpose of the gearing system was to drive the camera in phase with the input driving force and to match fluid velocities near the wall. In order to design the gearing system, it was necessary to estimate the local displacement of fluid at different radial positions. An equation, analogous to equation (9), relating the local maximum velocity to the local displacement is

$$X_{max1} = U_{u,max1} T/\pi. \quad (15)$$

Figure 30. Frequency parameter, α , versus flywheel speed, rpm.

Empirical relationships for steady turbulent flow which describe the velocity profile are

$$\begin{aligned}
 U^+ &= y^+ & y^+ &\leq 5 \\
 U^+ &= 5.0 \ln y^+ - 3.05 & 5 < y^+ &\leq 30 \\
 U^+ &= 2.5 \ln y^+ + 5.5 & y^+ &> 30
 \end{aligned} \tag{16}$$

where

$$\begin{aligned}
 U^+ &= U_{u,\max}/U^*, \\
 y^+ &= yU^*/\nu, \\
 y &= R - r, \\
 U^* &= U_{\text{ave}} (f/2)^{0.5},
 \end{aligned}$$

and

$$f = 0.0791(N_{\text{Re,ave}})^{-0.25}.$$

These equations can be found in many textbooks on fluid mechanics. It is necessary to relate $U_{u,\max}$ and U_{ave} in order to solve these equations. One relation for steady turbulent flow is

$$U_{\text{ave}} \approx 0.8 U_{u,\max}. \tag{17}$$

The use of equation (17) can be criticized because the instantaneous velocity changes throughout the cycle even going through zero. Another possibility is the time average of equation (2) over half a cycle

$$U_{\text{ave}} = \frac{1}{T/2} \int_0^{T/2} U_{u,\max} \sin(2\pi t/T) dt = 2 U_{u,\max}/\pi$$

or

$$U_{\text{ave}} \approx 0.65 U_{u,\max}. \tag{18}$$

Equation (17) was used in the design calculations. Equations (10), (11), (15), (16), and (17) were solved simultaneously for $X_{\max 1}$ by choosing values of $N_{Re,u}$, α , and y^+ (see figures 31, 32, 33, and 34). An estimate of the distance from the wall where $X_{\max 1}$ occurs (see figure 35) was obtained by solving equations (16) and (17) for values of $N_{Re,u}$ and y^+ .

With an estimate of how far it is necessary to move the camera, it is possible to design a gearing system to do the job. The restrictions on the gearing system were the maximum length of travel of the camera carriage, the output to input ratio of the camera carriage, and the input displacement from the scotch yoke. The problem was to take the input displacement from the scotch yoke and translate it into the correct displacement of the camera. The basic equation which relates the camera travel to the other variables is

$$L_{cam} = X_{pis} G C R_{oi} / \pi D_g \quad (19)$$

where L_{cam} is the distance the camera travels, G is the gearing ratio, C is the output to input ratio of the camera carriage, R_{oi} is the output to input ratio of the Floyd Drive, and D_g is the pitch diameter of the spur gear. Equation (19) is derived by starting with the scotch yoke displacement and going through each part of the gearing system to see how each part changes the input it receives.

The first step in the design procedure was to size the gears. The value of C was determined by experiment and the value of D_g was determined by strength considerations. A large value of the scotch yoke displacement (which was calculated in the previous section), the

Figure 31. Local, maximum fluid displacement versus $N_{Re,u}$ and α for fixed dimensionless distance from the wall ($y^+ = 5$).

Figure 32. Local, maximum fluid displacement versus $N_{Re,u}$ and α for fixed dimensionless distance from the wall ($y^+ = 15$).

Figure 33. Local, maximum fluid displacement versus $N_{Re,u}$ and α for fixed dimensionless distance from the wall ($y^+ = 30$).

Figure 34. Local, maximum fluid displacement versus $N_{Re,u}$ and α for fixed dimensionless distance from the wall ($y^+ = 75$).

Figure 35. Distance from the wall versus $N_{Re,u}$ and dimensionless distance from the wall.

maximum camera travel, and an output to input ratio of one were selected or

$$G = \pi D_g L_{cam,max} / X_{pis,max} C. \quad (20)$$

With the gearing ratio known it was possible to calculate the distance the camera would have to move to follow the fluid at the centerline with an output to input ratio of one or

$$L_{max} = X_{pis} G C / \pi D_g. \quad (21)$$

Finally the output to input ratio of the Floyd Drive for different radial positions can be calculated by letting $L_{cam} = X_{max1}$ in equation (19) and substituting equation (21) into equation (19) to get

$$R_{oi} = X_{max1} / L_{max} \quad (22)$$

(see figure 36).

Figure 36. Output to input ratio versus $N_{Re,u}$ and dimensionless distance from the wall.

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