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LAPORAN PROJEK TAHUN AKHIR

A STUDY FALLING PARTICLES IN VARIOUS TYPES OF FLUIDS WITH DIFFERENT VISCOSITY

Disediakan Oleh

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ABSTRACT

In many kind of process, especially technical separation, there is always been a motion of particles in certain medium. The transferable of particles from one place to another make it easier for some system or process to meet its target. The medium can be anything that is like liquid or gaseous, weather it is in stationary or in motion. For example, the disposable ashes form gas medium, transformation of solid from wasted air, and also the recycle process to gain back the acidic fluid form chemical plantation.

Overall, there are many literatures that have been published for public knowledge, and there a lot of knowledge that can be gained from these journals about motion of fluid with a stationary immersed particle in it. All of the parameters and variables that related to this thesis are considerably useful to generate new ideas and new models of equations. The purpose of it is to get the variations of velocity and acceleration relatively with time and distance deviation.

In this thesis, a mathematical model was develop for a spherical particle falling in various type of liquid with different value of viscosity i.e. viscosity of acid acetic, $\mu_1 = 0.001095$ Ns m^2, alcohol, ethyl, $\mu_2 = 0.00192$ Ns m-^{2}, alcohol propyl. $\mu = 0.00164$ Ns m-^{2}, kerosene, $\mu = 0.00153$ Ns m-^{2}, mercury, $\mu = 0.001375$ Ns m-^{2}, and turpentine, $\mu = 0.001155$ Ns m-^{2}. The mathematical model was solved using the boundary conditions, the sum of all forces that acted on the spherical particle and some assumption has been made to solve the equations model. An expression was obtained, from which the velocity versus time was deducted for transient and steady state conditions. This result is a simulation of a fall particle in a heated fluid, but in order to get the mathematical solutions, the simulations was change to a falling particle in various type of fluid with different value of viscosity. The results that were obtained here maybe not as same as the experimental value if it was conducted, but think of how powerful a mathematical model is when it is applied to gain the result of an experiment that hasn't been done yet.

Dalam kebanyakan proses, terutamanya pada pemisahan teknikal, pergerakan zarah-zarah pepejal di dalam suatu medium sememangnya berlaku. Medium tersebut boleh merangkumi cecair atau pun gas dan ia boleh berada di dalam keadaan rehat atau bergerak. Contohnya seperti penghapusan habuk dari asap gas, pemindahan pepejal daripada air sisa dan juga proses mendapat balik asid daripada udara sisa bagi sesebuah loji asid.

Penulisan dan kajian yang menyeluruh telah dijalankan ke atas pergerakan zarah pepejal di dalam bendalir. Semua parameter dan dan pembolehubah yang terlibat dengan pergerakan zarah dalam aliran bendalir yang mepunyai kelikatan dan ketumpatan yang berbeza telahpun di ambil kira. Model persamaan bagi pergerakan zarah yang berada di dalam aliran larutan bendalir yang berbeza kelikatannya telah pun dikaji dan dibentuk. Hal ini bertujuan untuk mendapatkan perbezaan dari segi halaju dan seterusnya pecutan terhadap perubahan masa dan jarak.

Dalam kajian ini, sebuah penyelesaian modul matematik telah dibangunkan untuk zarah pepejal yang dibiarkan jatuh di dalam pelbagai larutan yang mempunyai kelikatan yang berbeza, seperti asid asetik, $\mu_1 = 0.001095$ Ns m^2, etil alkohol, $\mu_2 = 0.00192$ Ns m-^{2}, propil alkohol. $\mu = 0.00164$ Ns m-^{2}, kerosin, $\mu = 0.00153$ Ns m-^{2}, raksa, $\mu = 0.001375$ Ns m-^{2}, and turpentin, $\mu = 0.001155$ Ns m-^{2}. Model matematik yang dibangunkan adalah berdasarkan kepada keadaan lapisan sempadan zarah di dalam bendalir sama ada ianya pegun atau dalam keadaan bergerak. Daripada penyelesaian persamaan tersebut, satu graf halaju zarah pepejal melawan masa pergerakan zarah yang diambil untuk aliran laminar dan keadaan malar telah dilukis dan dianalisa keputusannya. Keputusan yang didapati adalah relatif kepada simulasi pergerakkan zarah pepejal dalam bendalir yang dipanaskan di dalam satu larutan yang sama tertapi berbeza suhu pada senggat-senggat yang ditetapkan. Keputusan yang didapati di dalam tesis ini mungkin tidak menepati dengan keputusan yang akan dapati di dalam ekperimen sebenar, tetapi bayangkan betapa bergunanya sesebuah model penyelesaian matematik apabila digunakan untuk mendapatkan keputusan ekperimen yang belum pernah dilakukan sebelum ini.

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LIST OF NOMENCLATURE

F_E = external force

F_B = buoyancy force

F_D = drag force

Re = Reynolds number

r = sphere radius

D = sphere diameter

m_P =mass of particle

$\frac{du}{dt}$ = the rate of velocity against time

g_c = centre of gravity

V = volume

C_D = coefficient of drag force

A_P = the surface area of solid particle

U = the velocity of solid particle

ρ = liquid density

D_P = diameter of solid particles

μ = liquid viscosity

CHAPTER 1

INTRODUCTION

1.1 Background

External flows past objects have been studied extensively because of their many practical applications. For example, airfoils are made into streamline shapes in order to increase the lifts, and at the same time, reducing the aerodynamic drags exerted on the wings. On the other hand, flow past a blunt body, such as a spherical particle, usually experiences boundary layer separation and very strong flow oscillations in the wake region behind the body.

In certain Reynolds number range, a periodic flow motion will develop in the wake as a result of boundary layer vortices being shed alternatively from either side of the particles. This regular pattern of vortices in the wake is called a Karman vortex street. It creates an oscillating flow at a discrete frequency that is correlated to the Reynolds number of the flow. The periodic nature of the vortex shedding phenomenon can sometimes lead to unwanted structural vibrations, especially when the shedding frequency matches one of the resonant frequencies of the structure. One example is the famous Tacoma Narrow bridge incident.

The fall velocity and the associate drag force of a single or multi particles plays a significant role in some of the system in our average daily life. The fall velocity and the drag on a single particle in an infinite, calm fluid are functions of particles size, shape and submerged specific weight, and the mass density and viscosity of the fluids.

In another case, flow design of vehicles covers many aspects, including external aerodynamic shape, engine inlets, internal flow of the engine and passenger compartments flow induced vibration and noise, combustion related fluid dynamics etc. In the vehicle design process drag is of major importance. This quantity incorporates contributions both from friction and pressure forces; however, their relative contributions vary with the type of vehicle.

From an aerodynamic point of view ground vehicles (cars, busses, trucks and trains) are more complicated than commercial aircraft since the bodies are bluff, there is relative movement between different parts of the vehicle (rotating wheels) and the flow is strongly influenced by the proximity to the ground. The flow includes unsteady longitudinal trailing vortices and several separated regions and most of the total drag is due to pressure drag. Flow design may incorporate the possibility for extended regions of laminar flows over the body and control of separation. The occurrence of separation and the structure of the wake are greatly influenced by ground effects and side winds which further complicate the design process.

The aerodynamic drag is one of the most important factors which will make road vehicles more energy efficient, and will for instance directly affect the travel distance of battery powered vehicles. An interesting development has started recently aiming at the possibility to actively control flows through the use of MEMS (Micro Electro-Mechanical Systems), i.e. sensors and actuators imbedded in the surface of for instance an aircraft wing.

1.2 Problem Statement

The fall velocity and the associate drag force of a single or multi particles plays a significant role in some of the system in our average daily life. The fall velocity and the drag on a single particle in an infinite, calm fluid are functions of particles size, shape and submerged specific weight, and the mass density and viscosity of the fluids.

Consider the relative motions between a particle and infinitely large volume of fluid. Since only the relative motion is considered, the following cases maybe covered

- A stationary particles in a moving fluid,
- A moving particles in a stationary fluids;
- A particle and a fluid moving in opposite directions;
- A particles and a fluid both moving in the same directions but at different velocities.

For a better aspect, let us consider submarine that is subjected to immerse in sea water. When a submarine attends to move in the sea, it will experiences 4 type of forces; drag, lift, thrust and gravitational force. Between these forces, only two of them are in interest in making this thesis, the drag and the gravitational forces.

The purpose of making this thesis is:

- To stimulate the fall of particle in a heated fluid by using a mathematical model equations for a spherical particle in various fluid of different viscosity.
- To study and describe the basic phenomena and some simple theory that may be used to estimate boundary layer properties.
- To distribute and rise an equations of drag of falling particles in water, a solid-liquid interactions.
- To analyze the phenomena of free-falling body in any fluid.

Studies related to spherical particles are available in analytical form for a limited range of Reynolds number (Goldstein 1929). However, for large values of Reynolds number, empirical and semi empirical equations based on vast amounts of experimental data have been proposed by various investigators. For nonspherical, there is a distant lack of analytical relationships. Several extensive data has been collected pertaining to the drag coefficient and fall velocity of such particles, but these data have not been put in an analytical form so that a direct solution for fall velocity and drag coefficient can be obtained. However, in this thesis we are only considering the low Reynolds numbers.

Fluids are an important part of life processes, from the blood in our veins and arteries to the oxygen in the air. The properties of fluids make plumbing, automobiles, and even fluorescent lighting possible. Fluid mechanics describes many processes that occur within the human body and also explains the flow of sap through plants. The preparation of materials often involves a fluid state that ultimately has a strong impact on the characteristics of the final product.

Scientists gain increased insight into the properties and behavior of fluids by studying their movement or flow, the processes that occur within fluids and the transformation between the different states of a fluid (liquid and gas) and the solid state. Studying these phenomena in microgravity allows the scientists to examine processes and conditions impossible to study when influenced by Earth's gravity. The knowledge gained can be used to improve fluid handling, materials processing, and many other areas in which fluids play a role. This knowledge can be applied not only on Earth, but also in space.

So in this thesis, I have been given a chance to study and discover the factors and behaviors when a particle falling vertically in various kind of fluids in a steady state conditions. The temperature gradient will be constant and some of small factors are neglected to ensure the smoothen of the experiment.

CHAPTER 2

METHODOLOGY

2.1 Introductions

To ensure that this study will meet its sufficient target, all the terms that are related to the title have been searched and the detail findings will be included in this thesis. There are lots of wonders and questions that need to be answered, and so the experiment that needs to be done in a precise order so that everybody could know understand the presentation itself just an instant of time. For further understanding, below are the overall orders of steps taken to finish this thesis.

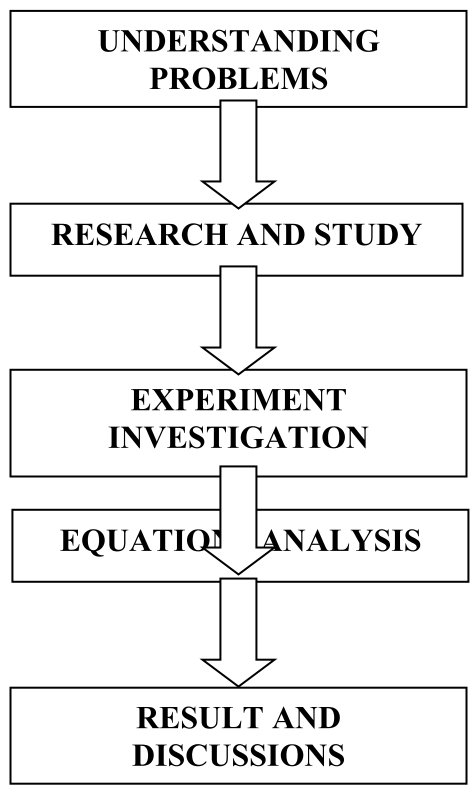

FIGURE 1: Schematic diagram on methodology of this thesis

2.1.1 Understanding Problems

From the beginning, the most important question that needs to be answered lies in the word 'Fluidity'. By then, the major aspect of the whole thesis has been brought out and the prior questions have been exposed. Problems are based on the behavior of fluid motion when it was immersed by a single particles that have certain and constant parameters like density, viscosity, and mass. The functions of these parameters will affect each and every other parameter in equations, resulting tremendous consequence for each of the behavior.

2.1.2 Research and Study

For the next steps, some journal and articles that related to this thesis were collected from the internet and as well as from the library, concerning about fluids mechanics and dynamics. Few notes from the past and present lectures also help to find more about the behavior of the motion of particles in fluids. Knowledge about this heading have been studied during first five weeks randomly just to know what is usually happen in particles that is immersed in fluid, the forces that acting on it, and the resultant action caused by that behavior.

Few examples of actual practice and situation that likely to go with falling particles when it immersed in moving fluid were already taken from some of collected journal of fluid motion. Their discussion of fluid performance helps to discover the actual conditions that were experienced by the particle. The value of drag coefficient and velocity were provided in some of the tables given with the journal. Also some of the content of this thesis were ideas of some lecturers, especially the supervisor, Prof Madya. Dr. Jalal Abdullah Aziz from School of Mechanical Engineering. The supervision that they have given makes it easier for this thesis to meet it success.

2.1.3 Experiment Investigation

After few weeks searching, finding, reading, and understand the concept of falling particles, some of the earlier experiment have been viewed and analyzed. Some of the result helps to gain knowledge and understand what are the fundamental and parameter that need to be found. There are a lot of equations that need to be understood but some of them are not too detailed and no solutions are included. The experiment is too costly and need and intensive observations to be managed, because of that there is no actual experimental that has been done during this thesis, and all the procedure and result have been adapted from several sources of journals and early lab experiment in School of Chemical Engineering, University Sains Malaysia, Pulau Pinang.

The procedure was according to this one experiment that was held in one of School of Chemical Engineering lab in USM Engineering Campus. Actually the experiment is all about comparison of drag coefficient of a sphere in two kinds of liquids, glycerol and lubricating oil with different kind of temperature variation. But in this thesis, there was a sufficient data that help to understand the properties of flow activity of fluids. Below is the overall procedure to complete the experiment of falling particles in fluid.

2.1.4 Equations Analysis

Actually the model of equation is taken from the definite experiment above. From the theory background and real conditions of falling particles in fluids, some forces was considered important and the stability of forces must be zero for particles to move constantly without any varying of its velocity. From these circumstances, the equations were built and it was tested to match its target; that is to investigate the affect of viscosity to its velocity gradient. The overall equations that have been set can be seen in Chapter 6.

2.1.5 Result and Discussions.

After some observations, analysis and discussions of all the data that have been taken in the experiment, a few deliberations and conclusions have been made. Some of the result may look different from its theory background, but it is considerably the best ideas that can be brought up to the public for renovations for the good use of community. In enormous process that involved motion of particle in stationary fluids, the particles were depended on size, shape, and condition when it was immersed in fluids. So there was a lot to reconsider when this thesis was in progress. Hopefully there is something useful statement that will help others to continue this study for further development.

CHAPTER 3

LITERATURE REVIEW

Over the years, many association and organization of science has discovered and developed the way to study about the behavior of falling particles in various kinds of fluids. Their research has made remarkable discovery and teaches a lot of new things that are aware before.

In 1904, Prandtl [1] proposed that external flows could be treated by considering two main regions, namely one next to the surface where viscous and friction effects are important and further away form the surface where viscous forces can be neglected. The idea behind this division is that viscous effects and friction are directly proportional to velocity gradients. In aerodynamic shapes the friction and viscous effects are restricted to a thin region next to the solid surface.

Blasius, a student under Prandtl, solved the nonlinear laminar boundary layer equations as part of his PhD dissertation [S. Goldstein, Modern Developments in Fluid Dynamics, Oxford, NY, 1938]. The boundary layer thickness, at a given axial location on the flat plate, is defined as the distance from the wall point at which the velocity is 99% of the far stream velocity, and according to Blasius' results it is given by:

$$\frac{\delta}{x} = 4.96 \operatorname{Re} y_x^{-\frac{1}{2}}$$

Solution methods for similarity solutions for flow over a flat plate are presented for two cases of boundary layer flow over flat plates: forced convection over a horizontal flat plate and natural convection over a vertical flat plate in a quiescent fluid. The solution for the forced convection case is a simple Euler method numerical integration. This solution proves to be robust over a range of grid spacing and Prandtl numbers.

The free convection solution failed to produce any results and needs further development. Two solutions were attempted for flat plate boundary layer flow: forced flow over a horizontal plate, and natural convection on a vertical flat plate.

The forced convection solution produced excellent agreement with a reasonably low number of grid points. In addition, the solution appeared stable over a reasonably wide range of conditions. Free convection on a vertical surface is a more unstable problem. The momentum and energy solutions are coupled, and the Euler method does not handle the problem well. An attempt was made to implement Ostrach's [2] solution, but the implementation was faulty and results could not be generated in time for this report.

An investigation of the interaction between gas porosity and a planar solid/liquid (SL) interface is reported by Niranjan Sahoo, et.al [3]. A two-dimensional numerical model able to accurately track sharp SL interfaces during solidification of pure metals and alloys is proposed. The finite-difference method and a rectangular undeformed grid are used for computation. The SL interface is described through the points of intersection with the grid lines. Its motion is determined by the thermal and solute gradients at each particular point. Changes of the interface temperature because of capillarity or solute redistribution as well as any perturbation of the thermal and solute field produced by the presence of non-metallic inclusions can be computed. To validate the model, the dynamics of the interaction between a gas pore and a solidification front in metal alloys was observed using a state of the art X-ray transmission microscope (XTM). The experiments included observation of the distortion of the SL interface near a pore, real-time measurements of the growth rate, and the change in shape of the porosity during interaction with the SL interface in pure Al and Al-0.25 wt pct Au alloy. In addition, porosity-induced solute segregation patterns surrounding a pore were also quantified.

The terminal velocity of irregular particles in a free-falling stream has been measured experimentally by C. Losenno and W.J [4].Easson using Particle Image Velocimetry. The aim of the measurements was to assess the influence of particle shape on the particle dynamics and compare the results with spherical particles. Measurements were carried out by using coarse glass powder and spherical glass beads of the same density and similar size distribution. Particle diameters ranged from 150 μm to 180 μm. Measurements were taken at both the developing region and self-similar region of the particles stream, as shown in Figure 1.

Detailed particle velocity information for both spherical and irregular particles was obtained. Significant differences between the behavior of spherical and irregular particles were observed at both stream locations. Terminal velocity of irregular particles has been found to be smaller than the velocity of spherical particles at all the measurement points.

The experimental results have been compared to empirical data. The drag coefficient of irregular particles has been found to be higher than both the predicted and experimental drag coefficient of spherical particles. The sphericity of irregular particles was found to be equal to 0.6.

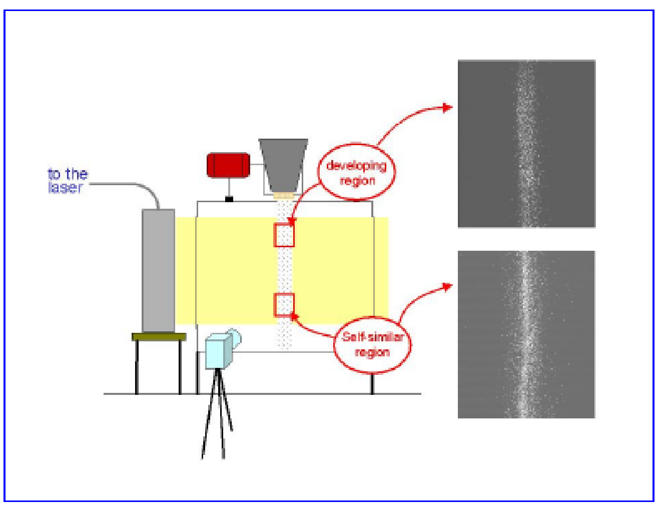

FIGURE 3.2: Experimental set-up and measurements locations

The terminal velocities of irregular and spherical particles in a free falling stream have been measured experimentally in the developing region and in the self-similar region. Experiments were performed using a Particle Image Velocimetry technique. Data presented includes profiles of mean velocity and fluctuation velocity. Experimental measurements showed that significant differences in the velocity profiles occur due to particle shape. In the developing region, the velocity of irregular particles showed a distinct peak in the centerline of the flow, whilst spherical particles exhibits a nearly flat radial profile. In the self-similar region, the terminal velocity of spherical particles evolves into a more pronounced profile with higher values in the jet centerline. However the biggest difference between velocity at the flow edges and centerline was found for irregular particles.

The experimental data is in good agreement with the empirical correlations of Haider and Levenspiel. In the stream centerline, the drag coefficient of irregular particles approached the drag of spherical particles. In the jet edges, the observed dynamic behavior of the particles in the stream moved towards the one of unbounded particles. The drag coefficient of irregular particles nearly doubled the drag of spherical particles at the stream edges and equaled the empirical drag coefficient for sphericity $\Phi=0.6$.

There is also another experiment held concerning about aerodynamic coefficient. Miniature three-component accelerometer balance system for measuring the fundamental aerodynamic force coefficients over blunt bodies has been designed, fabricated and tested in the Indian Institute of Science hypersonic shock tunnel HST2 at a nominal Mach number of 5.75 [5]. The model and the balance system are supported by rubber bushes, thereby ensuring unrestrained free-floating conditions of the model in the test section during the flow duration. The internally mountable accelerometer balance is used to measure the drag, lift and pitching moment coefficients for a 60° apex angle blunt cone within the effective tunnel test time of 800 μs. The measured aerodynamic force coefficients match very well with the theoretical values predicted using modified Newtonian theory at moderate specific enthalpy levels of the test gas.

Numerical solutions of stationary flow resulting from immersion of a single body in simple shear flow are reported for a range of Reynolds numbers. Flows are computed using finite-element methods. Comparisons to results of asymptotic low-Reynolds number theory, experimental study, and other numerical techniques are provided. Results are presented primarily for isotropic bodies, i.e. the circular cylinder and sphere, for both of which the two conditions of a torque-free (freely-rotating) and fixed body are investigated.

Conditions studied for the sphere are $0<Re<100$, and for the circular cylinder $0<Re<500$, with the shear-flow Reynolds number defined as $Re= \dot{\gamma}a2/v$; $\dot{\gamma}$ is the shear rate of the Cartesian simple shear flow $\boldsymbol{u} = (\dot{\gamma}y, 0, 0)$, a is the cylinder or sphere radius, and v is the kinematics viscosity of the fluid. In the torque-free case, the rotation rate of the body decreases with increasing Re. Qualitative dependence, seen in the Re=0 fluid flow field, upon whether the body is fixed against rotation or torque-free vanishes as Re increases and the fluid flow is more similar to that around the fixed body: the influence of rotation of the body and the associated closed streamlines are confined to a narrow layer about the body for $Re>O(1)$.

Separation of the boundary layer is observed in the case of a fixed cylinder at $Re\approx85$, and for a fixed sphere at $Re\approx100$; similar separation phenomena are observed for a freely rotating cylinder. The surface stress and its symmetric first moment (the stresslet) are presented, with the latter providing information on the particle contribution to the mixture rheology at finite Re. Stationary flow results are also presented for elliptical cylinders and oblate spheroids, with observation of zero-torque inclinations relative to the flow direction which depend upon the aspect ratio, confirming and extending prior findings.

Another approach on sedimentation of particles has been made. S. BonischV. Heuveline [6] Numerical Analysis group, IWR, University of Heidelberg, 69120 Heidelberg, Germany have presented a numerical scheme for the simulation of the steady, translational sedimentation of a single solid body in a non-Newtonian fluid of second-order type. This investigation is motivated by the problem of the orientation of falling particles in non-Newtonian liquids which finds its roots in various engineering applications such as flow-induced microstructures, manufacturing of short fiber composites and separation of macromolecules by electrophoresis.

The proposed approach is based on a reformulation of the conservation and kinetic equations in the body frame as well as a solver oriented toward the determination of steady state solutions of the underlying fluid-structure coupling. Unstable solutions are filtered out by means of a numerical linearized stability analysis with respect to the body equations. Numerical experiments are presented and validate the proposed approach.

A typical colloidal suspension is composed of particles between a few nanometers and a few micrometers in diameter suspended in a viscous Newtonian Fluid whose molecules are much smaller than the suspended particles. Robert B. Jones and Ramzi Kutteh Department of Physics, Queen Mary and Westfield College, Mile End Road, London, UK [7] describe a practical approach for computing the mobility matrix of a system of colloidal particles near a hard wall. The approach can be carried out in principle to arbitrary accuracy and number of particles. They make use of this approach to perform Stokesian dynamics computer simulations of colloidal suspensions in both unbounded and bounded Fluids. We study finite clusters of particles sedimenting parallel to a nearby hard wall under the influence of a uniform force. The convergence properties of the new scheme, the effect of the wall on the colloidal dynamics, and the additional effect of interparticle and wall-particle potentials are all examined.

In March of 2003, the Army Research Laboratory [7] conducted a 1-week Urban Experiment to challenge the current understanding of the surface layer stability transition and airflow around a two-story rectangular building. This Experiment was, in part, an extension of the ongoing Surface Layer Stability Transition Forecasting effort. The Experiment design was based on published wind tunnel measurements simulating airflow around a variety of model building sizes. Using wind tunnel results as a forecast of airflow features, the wind tunnel parameters were enlarged for the given building and the orientation was proportionately skewed for prevailing winds. Finally, four 10m meteorological towers were installed in specific locations along the building's North, Northeast, South, and Southwest sides. These ground layer towers reported standard meteorological parameters at the 2m and 10m levels. An additional 5m tower sampled the atmosphere above the roof.

Preliminary results confirmed, visually and quantitatively, the presence of the forecasted cavity flow, a bi-level accelerated flow between buildings, and the anticipated prevailing wind direction. The stability transitions were greatly influenced by the inhabited building. Unlike the forecasted stability transitions for an open desert, these urban environment transitions were not always evident. In fact, there were times when the daytime unstable surface layer persisted well into the traditional stable nighttime periods. Lessons learned and recommendations for improving future urban measurements / forecasting methods conclude this paper.

MF.Piva and S Gabbanelli[8], Grupo de Medios Porosos, Facultad de Ingenier´ıa, Universitas de Buenos Aires, study the motion of a single polymer chain settling under gravity in an ensemble of periodic, cellular flow fields, which are steady in time. The molecule is an elastic dumbbell composed of two beads connected by a nonbendable Hookean spring. Each bead is subject to a Stokes drag and a Brownian force from the flow. In the absence of particle inertia, the molecule settles out at a rate which depends on three parameters: the particle velocity in a fluid at rest, Vg, the spring constant, B, and the diffusion coefficient, D.

They investigated the dependence of the molecule settling velocity on *B*, for fixed *Vg* and *D*. It is found that this velocity strongly depends on *B* and it has minimum value less than *Vg*. They also find that the molecule is temporarily trapped at fixed points for certain values of the parameters. They analyze one fixed point in detail and conclude that its stability is the main factor which contributes to slowing down the settling process.

Another experiment on active control of flow over a sphere has been held lately by Sejeong Jeon, Jin Choi, Woo-Pyung Jeon, Haecheon Jeon and Jinil Park [9] from Seoul National University, and Ajou University. At $Re=10^5$, active control of flow over a sphere based on the free-stream velocity U_∞ and sphere diameter *d*, is carried out for drag reduction using a time-periodic blowing and suction from a slit on the sphere surface.

The forcing frequency range considered is one to thirty times the natural vortex-shedding frequency. With the forcing, the drag on the sphere significantly decreases by nearly 50% for the forcing frequencies larger than a critical frequency (about $2.85U_\infty$/d). For the forcing frequencies smaller than this critical frequency, the drag is either nearly the same as, or slightly smaller than, that without forcing.

The critical forcing frequency is found to be closely associated with the onset of the boundary-layer instability. It is shown from the surface-pressure measurement, surface oil-flow visualization and near-wall stream wise velocity measurement that the disturbances from the high-frequency forcing grow inside the boundary layer and delay the first separation while maintaining laminar separation, and they grow further along the separated shear layer and high momentum in the free stream is entrained toward the sphere surface, resulting in the reattachment of the flow (thus forming a separation bubble above the sphere surface) and the delay of the main separation. The reverse flow region in the wake is significantly reduced and the motion in that region also becomes weak owing to the forcing. Finally, the variation of drag by the present forcing with respect to the Reynolds number is very similar to that by dimples on the surface, but is different from that by surface roughness.

In Faculty of Chemistry, University of Sofia, Bulgaria, several lecturers beginning to study about the general problem of the friction felt by a spherical solid particle which moves parallel to the membrane of a spherical vesicle. An experiment has been carried out by R. Dimova, C. Dietrich, A. Hadjiisky, K. Danov and B. Pouligny [10] with SOPC vesicles at room temperature, with different particle and vesicle sizes. Experimental data show considerable finite-size effects whenever the particle is not very small compared to the vesicle. These effects are found consistent with the hydro dynamical theory of the vesicle-particle problem. This agreement allows for a robust determination of membrane viscosity, independently of particle and vesicle sizes.

Aerodynamics of trucks and other high sided vehicles is of significant interest in reducing road side accidents due to wind loading and in improving fuel economy. Recognizing the limitations of conventional wind tunnel testing, considerable efforts have been invested in the last decade to study vehicle aerodynamics computationally. Due to this, a three-dimensional near field flow analysis has been performed by Subrata Roy and Pradeep Srinivasan [11], for axial and cross wind loading to understand the airflow characteristics surrounding a truck like bluff body. Results provide associated drag for the truck geometry including the exterior rearview mirror. Modifying truck geometry can reduce drag, improving fuel economy.

Viscosity experiments using Ostwald-type gravity flow viscometers [12] are not new to the physical chemistry laboratory. Several physical chemistry laboratory texts (1 - 3) contain at least one experiment studying polymer solutions or other well-defined systems. Several recently published articles (4 - 8) indicated the continued interest in using viscosity measurements in the teaching lab to illustrate molecular interpretation of bulk phenomena. Most of these discussions and teaching experiments are designed around an extensive theory of viscous flow and models of molecular shape that allow a full data interpretation to be attempted. This approach to viscosity experiments may not be appropriate for all teaching situations (e.g., high schools, general chemistry labs, and nonmajor physical chemistry labs).

A viscosity experiment is presented here that is designed around common seed and vegetable oils. With the importance of viscosity to foodstuffs and the importance of fatty acids to nutrition, an experiment using these common, recognizable oils has broad appeal.

The micro-scale experiments focused on the motion of pairs of spherical particles settling in close proximity. By dropping large, easily-viewed particles in high-viscosity liquids, similar Reynolds numbers to these experienced in the macro-scale experiments could be achieved. The particles were large enough for micro-scale behavior such as the particles' mutual orientation to be observed.

The experiments were carried out in a square cross-section100 x 100 mm glass tank, with a height of 500 mm. A glycerol/water solution with a concentration about 80% glycerol by weight was used. Four different spherical plastic particles were used, sized from 3.175 mm to 9.35 mm as listed.

Macro-scale			Micro-scale			
d	u_s	Re	d	d^*	u_s	Re
1.0	0.058	26.4				
0.710	0.041	13.3	9.525; Y	1	0.096	17.7
0.500	0.027	6.2	6.350; X	0.666	0.044	5.5
0.355	0.017	2.7	4.763; X	0.5	0.028	2.6
0.250	0.010	1.1	3.175; X	0.333	0.014	0.8

Particle sizes d (mm), expected lone-particle settling speeds u_s (m s^{-1}) and Reynolds numbers, compared in the macro- and micro-scale experiments. For the micro-scale experiments, the largest particle's diameter (9.525 mm) was defined as the length scale, so $d^* = d/9.525$ mm.

FIGURE 3.3: The particles were precision ball bearings.

The overall fall was timed with a stopwatch and the dynamics of the interaction was recorded on videotape. Horizontal lines were marked on the tank faces both behind and in front of the falling particles. Thus the particle location could be accurately measured, taking parallax into account, to less than 0.5 mm. The Hi-8 video recording used the PAL system, enabling a time resolution of 1/25 s. In practice, it was possible to determine when a particle crossed a line between two consecutive frames, giving an effective temporal error of ± 0.01 s and a speed error of about $\pm 0.0008\ ms^{-1}$.

John Happel [13], from New York University, New York has written a journal about viscous flow in multiparticle systems: slow motion of fluids relative to beds of spherical particles. A mathematical treatment is developed on the basis that two concentric spheres can serve as the model for a random assemblage of spheres moving relative to a fluid. The inner sphere comprises one of the particles in the assemblage and the outer sphere consists of a fluid envelope with a "free surface." The appropriate boundary conditions resulting from these assumptions enable a closed solution to be obtained satisfying the Stokes-Navier equations omitting inertia terms. This solution enables rate of sedimentation or alternatively pressure drop to be predicted as a function of fractional void volume.

Comparison of the theory is made with other relationships and data reported in the literature. Of special interest is its close agreement with the well known Carman-Kozeny equation which has been widely used to correlate data on packed beds as well as sedimenting and fluidized systems of particles. This is remarkable in view of the fact that the force on each particle in a packed bed can be up to several hundred times that exerted on a single particle in an undisturbed medium.

Fluids Laboratory for Aeronautical and Industrial Research (FLAIR), Monash University, Victoria, Australia has made a study about interference drag between spherical and cylindrical particles in Stokes flow by A.K.W. Cheung, B.T. Tan, K. Hourigan , and M.C. Thompson [14]. In this study, predictions are made for the interference effects when two cylinders or two spheres are placed in series or parallel in a low Reynolds number flow. Using a spectral element method, it is predicted that for two cylinders with their line of centres perpendicular to the flow, the drag force is lower than the isolated cylinder case at small gaps but is greater at all other gaps; a maximum is found at a gap of approximately of 7 cylinder diameters.

The result is fundamentally different to the case of two spheres with their line of centers perpendicular to the flow, which has an analytical value reported in Happel and Brenner [15]; in that case the drag force on each sphere is less than an isolated sphere at all gaps. For cylinders with their lines of centers parallel to the flow, the drag on the trailing body is less than the leading body, which in turn is less than the drag on an isolated cylinder. In the case of spheres, the drag on the individual bodies is similar and less than the drag on an isolated body for all gaps. However, in the case of cylinders, the drag on the leading body is significantly greater than that on the trailing cylinder.

Several experiment concerning dimensionless parameters of falling particles in fluid is also available in reading materials and journals. One of them was the experiment held just to see the application of dimensional analysis to obtain dimensionless parameters that reduce the number of variables needed to represent a physical process. The physical process in this laboratory experiment is the drag (resistance) force on spheres moving through a fluid. In the experiments, the rate at which spheres fall through liquids was measured. Using dimensional analysis, the results apply equally well to spheres falling through gases instead of liquids or light spheres rising through gases or liquids. The results of these experiments and any others should be used only within the same range of dimensionless variables for which the tests are done.

The theory section summarizes some concepts of objects moving through fluids. These flows are sometimes called external flows, since the fluid is outside of the object. Internal flows are flows in pipes and ducts. The apparatus consists of three cylindrical tubes, each containing a different liquid. The density and viscosity of each liquid are known. There are also spheres of known diameter and specific weight.

FIGURE 3.4: Laboratory Apparatus of dimensionless parameters experiment

Paul A. Hwang [16], Air-Sea Interaction Lab., Univ. of Delaware, and Lewes wrote one in a journal that the instantaneous velocity of particles driven by an oscillating flow can be determined by means of Fourier analysis. A simple numerical method based on the principle of least square error is presented to obtain the solutions of the Fourier coefficients. The computed zeroth harmonic term, which is the effective fall velocity and is less than the terminal velocity in still fluid, is in good agreement with experimental observations. The reduced velocity is caused by the nonlinear modification of the drag force exerted on the particle by the fluid because the relative velocity between the particle and the fluid is no longer the constant terminal velocity.

There are three parameters that determine the effectiveness of fall velocity reduction: the terminal velocity Reynolds number, the ration of the flow velocity amplitude to the terminal velocity, and a quantity characterizing the frequency response of the particle to the unsteadiness of the flow motion.

The Doppler flow meter [17] measures the velocity of particles moving with the flowing fluid (Figure 3a). Acoustic signals of known frequency are transmitted, reflected from particles, and are picked up by a receiver. The received signals are analyzed for frequency shifts (changes), and the resulting mean value of the frequency shifts can be directly related to the mean velocity of the particles moving with the fluid. System electronics are used to reject stray signals and correct for frequency changes caused by the pipe wall or transducer protective material. Doppler flow meter performance is highly dependent on physical properties such as the liquid's sonic conductivity, particle density, and flow profile. Likewise, nonuniformity of particle distribution in the pipe cross section results in a computed mean velocity that is incorrectly weighted. Therefore, the meter accuracy is sensitive to velocity profile variations and to distribution of acoustic reflectors in the measurement section.

Unlike other acoustic flow meters, Doppler meters are affected by changes in the liquid's sonic velocity. As a result, the meter is sensitive to changes in density and temperature. These problems make Doppler flow meters unsuitable for highly accurate measurements.

The continuity equation and the simplified version of the time dependent boundary layer momentum and energy equations are solved simultaneously for flow between two parallel plates, using an explicit numerical procedure. Solving the three equations simultaneously eliminates the need to assume the shape of the velocity and temperature profiles. Furthermore, this approach provides a picture of the variation of the velocity and temperature within the entire channel. The steady-state solution is obtained by letting time become very large. The shape of the velocity and temperature profiles seems to be consistent with theoretical expectations.

The velocity and temperature profiles become fully developed at approximately $x/a = 0.05\,Re$ for $Pr = 1$, as expected. The average Nusselt number Nu in the fully developed region is computed to be 7.35 for the case of constant surface temperature and 7.93 for the case of the constant heat flux.

CHAPTER 4

BACKGROUND THEORY

4.1 Introductions

A study of external flow is particular importance having been quite an analysis to the aeronautical engineer in the analysis of air flow around the various component of an aircraft. In fact much of the present knowledge of external flows has been obtained from studies motivated by such aerodynamic problems. There is, however, substantial interest by other engineers in external flows; the flow of fluid around turbine blade, automobiles, buildings, athletic stadiums, smokestacks, sprays droplets, bridge abutments, submarine pipelines, river sediment, and red blood cells suggest a variety of phenomena that can be understood only from the perspective of external flow.

It is difficult task to determine the flow field external to a body and the pressure distribution on the surface of a body even for the simplest geometry. To discuss this subject, consider low-Reynolds-number flows ($Re<5$, or so) and high-Reynolds-number ($Re>1000$). High-Reynolds-number flow can be subdivided into three major categories

a) Incompressible immersed flow involving such objects as automobiles, helicopters, submarines, low speed aircraft, take-off and landing of commercial aircraft, buildings, and turbines blades.
b) Flows of liquids that involve a free surface as experienced by ship or a bridge abutment;
c) Compressible flow involving high speed object ($V > 100$ m/s) such as missiles, aircraft, and bullets.